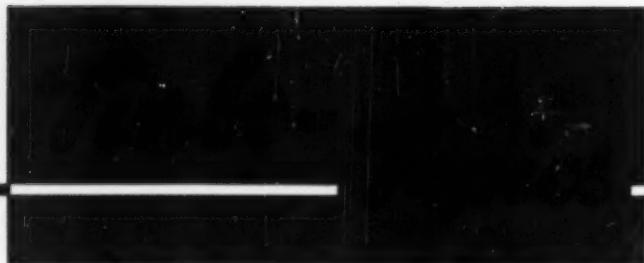


DECEMBER 1950

# Chemical Engineering Progress

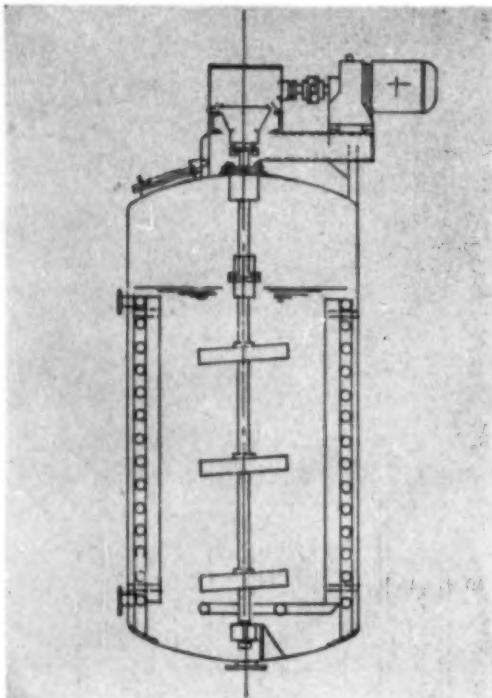
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# Chemical Engineering Progress

Volume 45

Number 12

DECEMBER  
1950

To all its readers Chemical Engineering Progress extends Christmas greetings and good wishes for a glad New Year.

**Taking Stock—Professionally**  
Shortly comes the time of stock-taking. Did you and we, for instance, collaborate in furthering the cause of chemical engineering in 1950? Did you submit that paper you were planning back in the early weeks of this year so that others could have the benefit of your experience?

Did you write that letter to the Editor constructively criticizing an author's conclusions, and pointing up at the same time a better engineering approach? Have you followed the reviews of books published in "C.E.P." and specially selected by the editors as the most important in your profession of chemical engineering?

Again, in 1950, the A.I.Ch.E. held four meetings. How many did you attend? What was your contribution to the many symposia? As many editorials as there are months in the year were published in 1950. These were written by leaders in the field, epitomizing years of experience, personal philosophy, and hardheaded conclusions. Engineering education, atomic research, the engineer's duty to society, were all covered. From these opinions were you able to cull something for your own betterment or success?

Our desire on "C.E.P." is to help. We often boast in the column that the best chemical engineers in the world are members of the A.I.Ch.E. We believe that sincerely, we know it to be true, and as you "belong" to the A.I.Ch.E., so A.I.Ch.E. "belongs" to you. As you develop, so the Institute, so your profession. So use 1951, use your profession, use your professional organization—the A.I.Ch.E., and like Ben Franklin's key, all will become bright.

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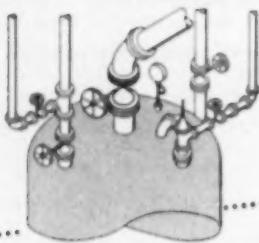
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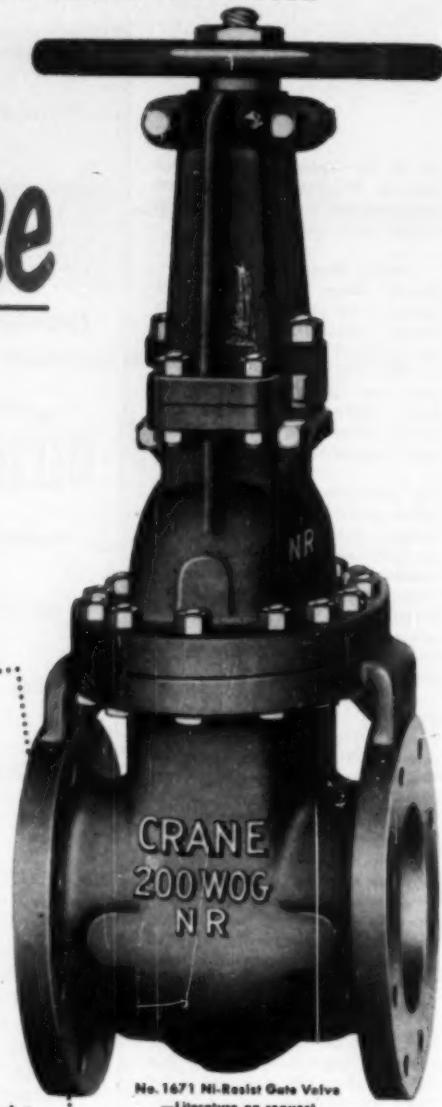
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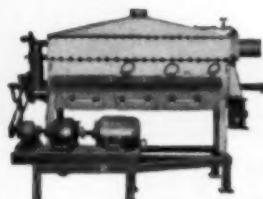
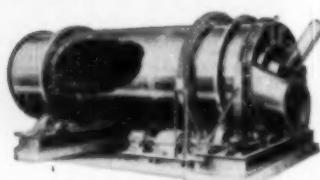
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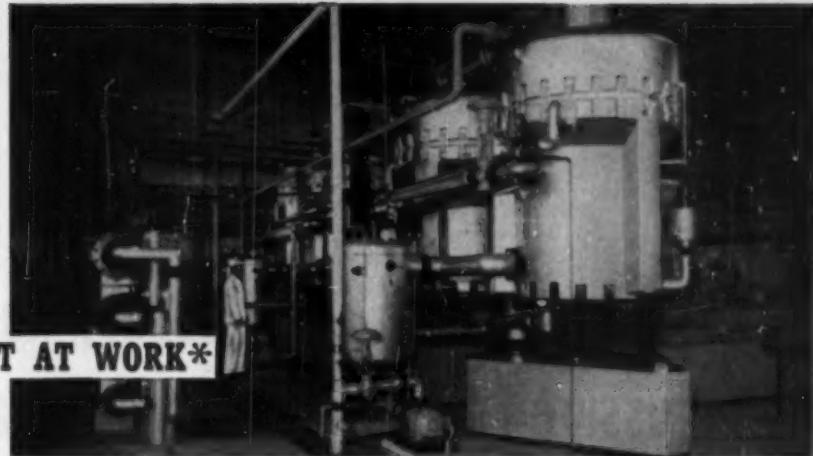
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clarification of suspensions*

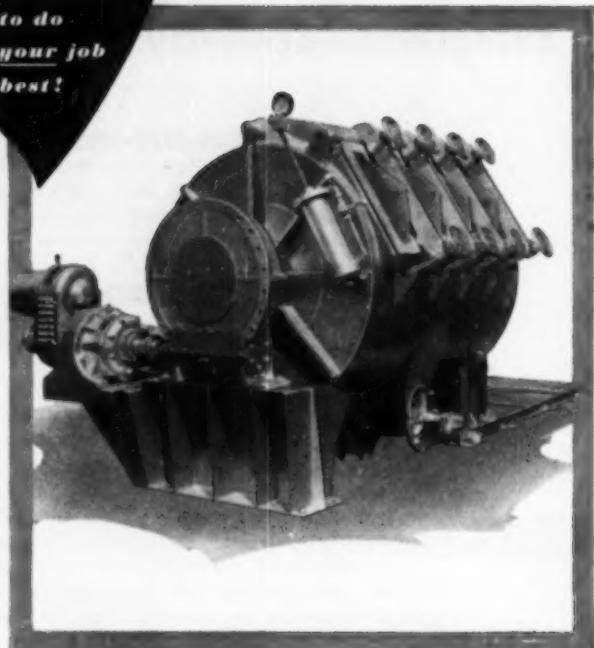
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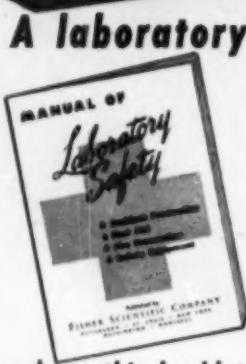
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This high-silicon iron elbow was subjected to thermal shock.



This plastic elbow discolored ethyl acetate.

This "KARBATE" impervious graphite elbow was:



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# OPINION AND COMMENT

## THE LOCAL SECTIONS AND THE INSTITUTE

PERHAPS the most enjoyable activity of the officers of the Institute is that of visiting local sections, attending local section meetings, and discussing with them the problems and policies of the Institute. During the past two years I have enjoyed the hospitality of nearly a score of our local sections, distributed over an area from coast to coast and from Minnesota to Texas.

My visits with them have strengthened my conviction that local sections are strong foundations of the Institute and are the sources of much of its strength. All sections that I have visited are vigorous and healthy, are increasing rapidly in membership, and are continually expanding their programs. Several trends in local section activities are especially interesting, and are worthy of comment.

1. Meetings are more varied in nature and more ambitious than ever before. For variety, programs are a blend of both technical and nontechnical subjects. Social events, plant trips, and combined student chapter-local section meetings are common. One-day meetings covering technical and nontechnical subjects, some of them approaching Regional Meetings in scope, are conducted by several of the larger sections. These meetings have been notably successful. The use of local speakers and of speakers and discussion panels drawn from the section membership is increasing. It is being discovered that the excellence of a speaker is not necessarily proportional to the distance he has travelled to the meeting.

2. Local sections are increasingly interested in the publications and publication problems of the Institute. Local sections can contribute directly to the Institute's publications by encouraging the submission of manuscripts and supporting advertising.

3. Local sections are beginning to supply expert and effective vocational guidance to students in local high schools, to students who are interested in scientific and technical careers. Activities in cooperation with other

local technical and engineering groups in the area of vocational guidance offer an opportunity for local section service.

4. The professional guidance of young chemical engineers is close to the hearts of most local sections. Junior members hold office and are active in all local section work.

5. Local sections are becoming more public relations-minded, and are beginning to be active in searching out qualified chemical engineers and encouraging them to apply for membership in the Institute.

6. An important function of local sections is to train men for national office in the Institute, and to see that qualified men are nominated and elected. A successful experiment was conducted this year by asking local sections to recommend specific candidates for Director, and all 12 candidates nominated for the term 1951-53 were suggested by local sections under this plan.

Progress is clearly evident in all local section activities. Local sections are functioning as miniature Institutes in their own localities, and their programs, taken in perspective, parallel closely those of the Institute.

Although the programs of the individual sections vary considerably, common principles underly the approach of all sections. It is recognized that a member of the Institute can get back only what members contribute. Local sections offer an opportunity of combining talents, background and knowledge, and thereby multiplying the effectiveness of the individual member. Section programs and accomplishments are clearly the result of local initiative and thought, under general guidance from the Local Sections Committee. No directives, financial burdens, nor regimentation is handed down to them from a centralized Institute authority. As long as these principles are defended and applied by the nearly 40 local sections, the American Institute of Chemical Engineers will continue to progress.

*W. L. McCabe, President, A.I.Ch.E.*

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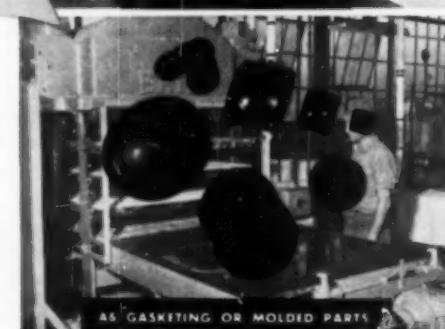


It's worth checking into — one of the many Tygon flexible plastic formulations may well provide the answer to your tough corrosive problems.



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# WASTE UTILIZATION AND DISPOSAL SYSTEMS

## COST STUDIES OF EVAPORATION AND DRYING

W. D. KOHLINS and E. L. DEMAREST

Blaw-Knox Company, Buflakov Equipment Division, New York, New York

METHODS of handling waste problems can be divided into two main categories. The first of these is the "civil engineering approach" which employs chemical treatment, trickling filters, lagooning, aeration and similar ways which tend to purify the effluents or render them less harmful. The second general category covers what might be called the "chemical engineering approach" whereby chemical engineering unit operations are applied to remove and/or recover the harmful constituents of the waste. This paper will deal entirely with the chemical engineering methods and will attempt to give cost data on several different types of waste disposal problems which have been successfully solved.

The chemical engineering waste disposal problem first breaks down into two major considerations; namely, whether or not a usable product can be recovered. If a salable product can be produced from the waste then the design of the equipment and cost of operation may be governed to a large extent by the chemistry and requirements of the product to be made. If no usable product can be derived from the effluent then the major concern is to remove the waste at the minimum over-all cost. A few examples may serve better to illustrate this point.

One of the oldest answers to a waste disposal problem has been the growth of the entire manufactured products division of the dairy industry. The production and development of evaporated milk, condensed milk, dried milk, whey, milk sugars and the many other derivatives of milk came about originally as the solution to a waste disposal problem when laws were passed banning the dumping of surplus milk or skim milk into the rivers. Here is a case of an entire industry growing out of the solu-

tion to a waste disposal problem. The production of glue, gelatin, fertilizers, vitamins and similar products from packing house wastes is another example of the building of a by-product industry from waste materials. The recovery and sale of feed material from distillers wastes and fish solubles are growing and profitable industries based on recovering waste.

Another profitable type of waste reclamation has been the reconstitution of used liquors for reuse in the same process. The concentration and burning of black liquor in the pulp mills and concentration and desalting of spin bath in the viscose rayon process are good examples of this type of operation. The distillation and recovery of solvents from residues of extraction processes are another example. Finally the reconstitution of waste pickle liquors with the attendant production of valuable by-products is an example of reclamation of process liquor plus the production of a salable product.

There is another type of disposal problem where no useful product can be made nor can a usable liquor or ingredient be returned for reuse in the process. Here the wastes must be disposed of for pollution reasons alone. The examples of this type problem are fewer since the ingenuity of the chemist and engineer has been pointed toward making something of nothing. However, there are many sludges and effluents which to date have no practical use but which must be disposed of for health and conservation reasons. Waste products from the nuclear fission plants are a fine and difficult example. Residues from explosive plants, organic chemical plants and electroplating operations often present this same type of problem.

Five specific waste problems will be considered, in some detail, in this paper.

Two involve treatment of wastes for disposal reasons only with no recovery of a salable product; two others deal with abatement of pollution plus the production of valuable by-products and the final problem involves disposal of a by-product of limited value. In all cases evaporation was used to remove the majority of the water present and in some instances the evaporator effluent was the final product. In other cases drying followed evaporation to put the product in a more salable or disposable form.

The costs assumed are given in Table A.

TABLE A—BASIS OF COST CALCULATION

Installed cost—double major equipment cost
Steam—\$0.70/lb. lb.
Water—0.01/M. gal.
Power—0.01/kw hr.
Labor—1.50/man-hour
Interest and depreciation—12%/year of total installed cost
Maintenance—3%/year of total installed cost
Operating year of 20 hr./day and 365 days/year unless otherwise noted.

### Fermentation Waste Liquors

In distilleries producing alcohol from grain, recovery of the distillers solubles from spent mash achieved widespread acceptance during the recent war. In practice whole slops from the still are first screened to remove coarse grains and hulls. These screenings are dried in steam tube dryers to produce a cattle feed. The filtrate which contains approximately 4%–5% total solids, of which about half are suspended and half in solution, is concentrated to approximately 30% total solids in multiple-effect evaporators and then dried by drum dryers or spray dryers (See Fig. 1.) The dry material is high in protein and riboflavin and is a premium animal feed. Previously this "thin slop" which has a high B.O.D. had been discharged into near-by streams.

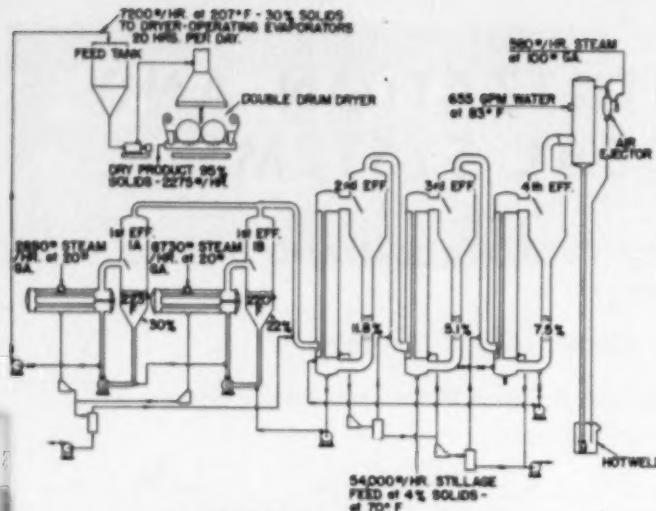


Fig. 1. Stillage processing equipment.

Production of a variety of antibiotics by fermentation processes also produces a waste liquor similar to that from the grain alcohol distilleries. It has been found that these wastes are subject to the same chemical engineering treatment with the same elimination of a serious pollution problem and the production of a valuable by-product.

From the engineering standpoint the major problems are the proper design of an evaporator to handle a viscous liquor with a high fouling characteristic, together with the selection of proper materials of construction to withstand the corrosive effects of the organic acids produced. Initially the evaporators were of cast iron through-

out; except for copper tubes, tube plates, and bronze pumps. Experience has indicated that stainless clad steel can be substituted for certain cast iron parts and that copper or stainless liquor and condensate piping are justified.

The specific problem analyzed here, involved the handling of 54,000 lb./hr. of distillery thin slop containing 4% total solids. This feed material was concentrated to 30% total solids in a five-body quadruple-effect evaporator of the long tube, natural circulation type for the last three effects, and forced circulation units for the first effects. This evaporator was of cast iron, stainless and copper construction. Four atmospheric double-drum dryers com-

plete with product-handling systems were required for drying the 30% concentrate to 5% final moisture. Cost data are shown in Table B.

TABLE B.—DISTILLERY SOLUBLES  
RECOVERY

Major equipment cost	\$224,000
Total installed cost	448,000
Annual operating cost:	
Steam—19,420 lb./hr.	\$ 99,100
Water—655 gal./min.	5,730
Power—66 connected hp.	3,580
Labor—3.5 man-hours (24 hr. day)	46,000
Interest and depreciation	46,000
Maintenance	13,440
Total	\$221,660

In this particular case, use of alloy materials is reflected in the relatively high carrying charges. It can be seen from these figures that although the investment is substantial, the cost per pound of finished product is low and allows ample margin for profit, at a current selling price of \$95/ton.

## Liquor from Rag-Cooking Operations

In the manufacture of vulcanized fibre, cellulosic materials are cooked in strong alkaline solutions. The result is a waste liquor containing alkali and organic materials. In the kraft pulp mills a similar liquor ("black liquor") is concentrated and then the alkali value recovered by burning in special recovery furnaces. For the vulcanized fibre industry the high cost of the special recovery furnaces cannot be justified for the small quantity of alkali recoverable. The alkali, however, still constitutes a serious stream pollution problem. Therefore the most satisfactory solution was to evaporate the residue before burning as shown in Figure 2. The evaporation step was simple and straightforward. After consideration of various drying methods, atmospheric double-drum drying was selected as the most economic. Preliminary tests yielded a gummy product that could not be handled easily. In the same plant there was a relatively large amount of dry powdered waste from machining and cutting operations of the finished product. It was found that the addition of a small amount of this dry waste to the concentrated cooking liquor modified its characteristics so that a dry, easily handled product was made on the drum dryer.

A specific problem involved the handling of 10,000 gal./day of waste "cooker liquor" containing 10% total solids. This material was concentrated to 40% solids, dry additive mixed with it, and the resultant mixture dried to 5% moisture. The equipment required was a double-effect long-tube natural circulation evaporator of carbon steel construction and an atmospheric double-

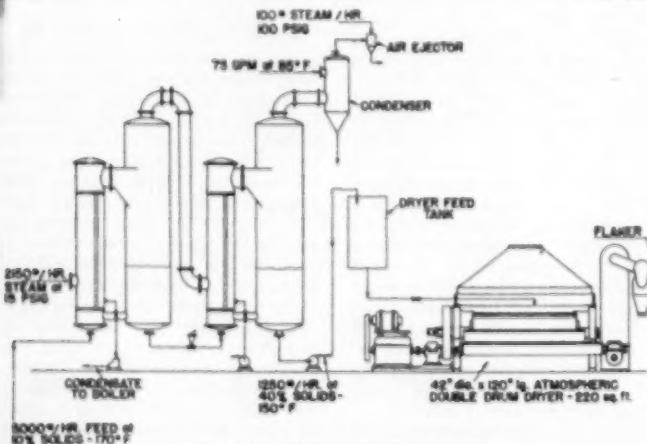


Fig. 2. Cooker liquor disposal system.

drum dryer. Cost data are given in Table C.

TABLE C.—COOKING LIQUOR DISPOSAL.

Major equipment cost	\$26,000
Total installed cost	\$8,000
Annual operating cost:	
Steam—3,150 lb./hr.	916,100
Water—75 gal./min.	660
Power—12 1/2 connected hp.	680
Labor—1-man-hour (54 hr. day)	13,100
Interest and depreciation	6,960
Maintenance	1,740
Total	\$33,240
Cost per gallon of feed liquor	\$0.0107
Cost per pound of finished product	0.0102

The plant in which this equipment was installed was ordered to stop polluting streams, and had originally considered chemical treatment. This would have resulted in partial abatement that would have been satisfactory, but it would have been only a question of time before complete abatement would be mandatory. By means of the system selected, complete abatement at reasonable cost was achieved.

### Fishing Industry Applications

Disposal of waste from fisheries has always been difficult. The largest fishing industry in the United States is devoted solely to the catching of menhaden.

Menhaden are usually processed immediately upon the arrival of the boat at the receiving plant. The fish are transferred from boat-hold to conveyor system, then to cookers where the cell structure is broken down with the aid of steam sparging. The cooked fish pass to a screw press, where the meal is freed from liquid. The meal is sent to steam tube dryers, where the moisture content is reduced to about 8%. The liquid from the press passes to centrifugals which accomplish oil separation and the aqueous layer (designated as "stick water") passes to storage tanks.

In the earlier days of menhaden fishing, the press water was discarded, resulting in highly objectionable conditions in the vicinity of the processing plants. It was subsequently discovered that the nitrogenous materials and vitamins present in the press water could be recovered by evaporation (Fig. 3), the resulting "stick" being a good source of nitrogen and vitamins for poultry and cattle.

Press water as fed to the evaporator is a cloudy, brownish solution containing about 7% solids. Up to concentrations of about 30%, the material remains quite fluid and can be evaporated with excellent success in vertical tube rapid circulation evaporators. At concentrations above 30%, viscosity increases rapidly and forced circulation units are preferred. The customary fish solubles concentrate contains 50% solids.

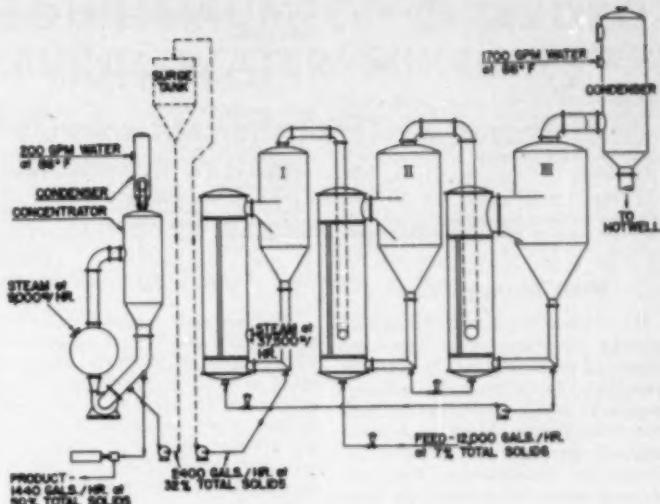


Fig. 3. Fish stickwater evaporator.

Cost data presented were furnished by an installation consisting of a triple-effect long-tube evaporator in steel and copper construction, fed 2-3-1, followed by a forced circulation single-effect unit to handle the more viscous material. This evaporator had a capacity of 12,000 gal. of press water/hr., producing 1440 gal./hr. of concentrated material.

As the fishing season varies in length from two to five months, the economic picture presented by the data given may change accordingly. For comparison, a year of 2000 operating hours has been selected. Any change in operating time

will be reflected in the unit cost, but it can be seen from Table D that ample margin exists between product value and operating cost.

Here is an instance in which the return on the investment and operating cost is so great that the production of condensed fish solubles is now considered a part of fish reduction plant operations and can scarcely be considered purely a waste disposal problem.

In this particular case the current selling price is \$0.05/lb. of 50% solubles; the value of the product from a 2,000-hr. season is \$1,375,000.

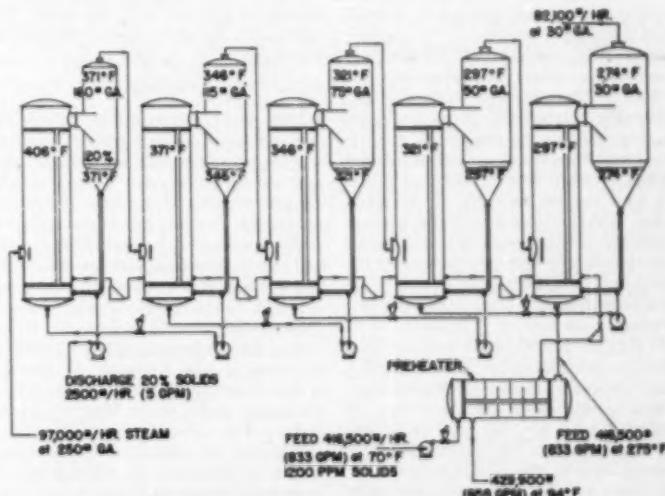


Fig. 4. Waste water evaporator. Metal-treating plant.

TABLE D.—FISH STICKWATER RECOVERY

Major equipment cost	\$ 95,000
Total installed cost	180,000
<b>Annual operating cost:</b>	
Steam—46,500 lb./hr.	\$ 64,960
Water—1,900 gal./min.	7,440
Power—7 connected hp.	105
Labor—1 1/2 man-hours	4,600
Interest and depreciation	23,800
Maintenance	5,700
Total	\$105,905
Cost per gallon of feed liquor	\$0.00425
Cost per pound of finished product	0.00885

### Metal-Treating Plants

Waste solutions resulting from metal-finishing operations are many and varied. The large majority contains heavy metal ions often not in sufficient quantity to justify recovery but in concentrations strong enough to be deleterious to plant and animal life if discharged into surface waters. Treatment of such wastes chemically has been practiced, but this is expensive. A more satisfactory method of disposal is to make use of a "transformer" evaporator, such as is used to produce boiler feed from brackish water.

The particular problem furnishing the following cost data (see Table E) arose in a large metals-finishing plant handling copper and cuprous alloy tubes, sheets, plates, etc. The waste solutions amounted to 1,000,000 gal./24-hr. day, and were of two varieties. The first waste solution contained copper, zinc and chromium, totaling 100 p.p.m., and sulfuric acid in amounts varying from 100 to 500 p.p.m. The second type of waste liquid contained soaps, mineral oil, saponifiable oil, cyanides and about 500 p.p.m. combined alkali.

These solutions were produced in such quantities that they nearly neutralized each other, but due to the presence of cyanide, careful pH control was necessary. After neutralization, the dilute solutions are sent through multiple-effect evaporator, shown in Figure 4, thus reducing the volume and producing steam for process use. Concentrated solutions were sent to refining plants by tank car for recovery of the metal ions. Further reduction of this concentrate by drying was not considered feasible since it was anticipated that the recovery operation would ultimately be transferred to the point of waste production.

Cost data presented are in connection with a quintuple-effect natural-circulation evaporator in all steel construction, reducing the 1,000,000 daily gal. of waste solution to 7,500 gal. Evaluation of the economics of this operation is complicated by the fact that low pressure steam and pure water (essentially distilled) are by-products of operation,

and their value must be taken into consideration.

TABLE E.—METAL-TREATING PLANT WASTE WATER DISPOSAL

Major equipment cost	\$190,000
Total installed cost	380,000
<b>Annual operating cost:</b>	
Steam—97,000 lb./hr. at 250 lb./sq. in.	\$495,000
Water—None	
Power—32 connected hp.	2,830
Labor—1 1/2 man-hours	16,400
Interest and depreciation	45,600
Maintenance	11,400
Total	\$571,230
Cost per gallon of feed	\$0.00156

This evaporator produces, in addition to the 7,500 gal./day of concentrated metal solution, 82,100 lb./hr. of process steam at 30 lb. gage pressure and approximately 850 gal./min. of essentially distilled water. Assuming a value of low pressure steam at 47 cents/M lb., and pure water at 2 cents/M gal., the annual values of these products are:

Steam	\$282,000
Water	7,440
Total	\$289,440

The figure of 2 cents/M gal. of pure water was used in this calculation since there was no indication of the true value of this water to the manufacturing operation, and the only justifiable credit that could be taken would be the prevailing cooling water cost.

It can be seen from the above table that the steam cost for evaporation would be prohibitive under normal circumstances. By operating under the conditions selected, a large amount of process steam is produced, which is credited to the operation, hence reducing the net cost. Essentially distilled water is also produced. Crediting these as shown reduces the operating cost by approximately one half. No credit has been taken for the value of the metals recovered.

### Whey

The final problem to be considered involved whey, which is a water solution of milk sugar, albumin and various salts and has been for years a major waste disposal problem from cheese and casein operations. In fact, this is one instance where consumers of one product, casein, in order to obtain supplies of this product worked on and sponsored means of recovery of a secondary product, whey. Because the manufacture of casein involves the production of large amounts of whey it was necessary to develop means to produce a usable or disposable product from the whey. However, competition for casein has been keen and to obtain it the whey has to be handled. Dry whey has value as a feed additive as well as certain medicinal value. The concentration of the weak whey liquors

is of no special concern and is carried out in long-tube natural-circulation evaporators. However, the drying of the whey presented some major problems, particularly because of the high sugar content of some whey, particularly the casein whey. Special-type spray drying was developed to handle this product and a two-stage drum-drying procedure was patented which handled the casein whey satisfactorily. Cheese whey was not so difficult and could be drum-dried readily merely by allowing the dried product to accumulate for a short time before conveying or grinding.

A typical cheese whey plant had to handle 18,000 lb./hr. of a 6% whey solution. A triple-effect long-tube evaporator was installed to concentrate to 40% total solids. This product was treated to remove albumin and phosphorus and the filtrate further concentrated to about 75% solids in a flooded-type single-effect concentrator. The concentrated product was then dried on an atmospheric double drum dryer. Cost data are shown in Table F based on a 3,000 hr./year operation.

TABLE F.—WHEY RECOVERY

Major equipment cost	\$ 51,975
Total installed cost	102,750
<b>Annual operation cost:</b>	
Steam—6,525 lb./hr.	\$17,900
Water—270 gal./min.	971
Power—28 installed hp.	625
Labor—3 man-hours	6,000
Interest and depreciation	12,850
Maintenance	3,080
Total	\$40,926
Cost per gallon of feed liquor	\$0.00881
Cost per pound of finished product	0.0126

This problem serves to illustrate an intermediate point between the large-scale profitable distillery solubles recovery operation and the straight disposal problem presented by the disposition of rag-cooking liquor solids. In the manufacture of cheese or casein, whey is an unavoidable by-product and most state laws prohibit its disposal into surface waters. The tabulation (see Table F) indicates that it can be recovered at reasonable cost.

Cost data presented have thus indicated that waste disposal may be economically feasible when accomplished by the chemical engineering unit operations of evaporation and drying. In certain cases, the value of the treated product exceeds the cost of treatment. For those plants which can no longer dispose of their wastes by dumping, these techniques may be most economic even though the effluent has no value. Dry products which are easily disposable can be produced, and thus complete, and not partial, abatement obtained.

(Presented at Thirteenth Regional Meeting, Houston, Tex.)

# VAPOR-LIQUID EQUILIBRIUM OF C<sub>4</sub> HYDROCARBON-FURFURAL-WATER MIXTURES<sup>†</sup>

## Experimental and Theoretical Methods for Three- and Four-Component Systems

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PREDICTION of equilibrium relationships in nonideal multicomponent mixtures is of great importance when two or more materials are separated by distillation in the presence of extractive or azeotropic agents. Many cases of commercial interest involve the separation of only two components in the presence of a third separating agent; satisfactory correlation of results for such mixtures can often be made through use of various types of ternary equations. Gerster, Mertes, and Colburn (2) for example, correlated their vapor-liquid equilibrium data for pairs of C<sub>4</sub> hydrocarbons in dry furfural by means of three-suffix Margules equations. In many cases, however, the separating agent may consist of two components such as furfural-water, methyl ethyl ketone-water, or acetone-water, or there may be more than two components to be separated by a single separating agent. Four-component equations required for prediction of such systems have not been adequately tested, nor are sufficiently precise nonideal four-component equilibrium data available in the literature to make such a test conclusive.

Specific interest in mixtures of C<sub>4</sub> hydrocarbons, furfural, and water has continued since the large-scale plants producing butadiene by dehydrogenation of petroleum gases make a separation between the various butanes, butylenes, and butadiene by extractive distillation with furfural-water. Addition of water to the furfural solvent in these plants has been made to lower reboiler steam pressures since a furfural-water mixture boils at a lower temperature than at dry furfural alone were used.

The purpose of this study is to extend present knowledge of these systems in particular. Although a large number of C<sub>4</sub> compounds are present in the commercial mixtures, it was decided to begin

by carefully determining the equilibrium properties for a typical pair of C<sub>4</sub> hydrocarbons in wet furfural. By application of thermodynamically sound equations to the results, it was planned to determine the extent to which such prediction methods could be generally applied to a typical nonideal quaternary system.

The system chosen for the present investigation consists of mixtures of isobutane, 1-butene, water, and furfural. Isobutane and 1-butene were chosen as the typical C<sub>4</sub> hydrocarbon pair to be separated since they are available as pure components, do not form stereoisomers, have wide deviations from Raoult's law in the presence of furfural, and do not self-polymerize to any extent. Temperatures of 100°, 150°, and 200° F. were used, corresponding to values encountered in plant practice; the water content of the furfural was varied up to 6 wt. % or 25.4 mole %, representing values approaching the solubility limit for water in furfural. Concentration of the two C<sub>4</sub> hydrocarbons in the furfural-water ranged up to more than 20 mole %, corresponding to pressures of up to 100 lb./sq.in. gage pressure. The ratio of the two C<sub>4</sub> hydrocarbons was varied over the complete range.

Earlier work in these laboratories (2, 9) with the nonideal ternary systems isobutane-1-butene-furfural and n-butane-1-butene-furfural provided a sound basis for the experimental techniques and results of this study. The theoretical treatment for these ternary systems showed that if the binary equilibrium characteristics of each of the three binary mixtures comprising the ternary mixture were known, prediction of the ternary relationships could be made through use of the relatively simple three-suffix Margules equations, provided a few ternary measurements were made to establish the ternary effect. Since three-suffix Margules equations represented the least complicated form which could be used to describe the ternary systems, it was indicated that the same type of equations should be tested first for their ability to represent the quaternary data with the

hope that they would be of sufficient complexity. As will be shown later, these equations were found satisfactory, and no other type of equation was tested.

The three-suffix Margules equations for quaternary systems express the equilibrium characteristics of the system through constants which describe the equilibrium properties of the six binary pairs and four ternary mixtures which go to make up the quaternary system. Fairly precise knowledge of equilibrium data for the ternary systems isobutane-water-furfural and 1-butene-water-furfural were required for prediction of the quaternary system, and these data were also determined and reported in this paper. Use of these data was also helpful in establishing the validity of certain simplifications of the quaternary equations introduced later.

### Method

The same flow-type apparatus described by Mertes and Colburn (9) to determine equilibrium relationships in single C<sub>4</sub> hydrocarbon-furfural systems was modified for the present study. A stream of vapor of constant composition is passed through the liquid of the equilibrium chamber until the inlet and outlet vapor concentrations eventually become equal indicating that equilibrium is established. As before, the vapor passed through the liquid once, was condensed, and collected in a receiver. The equilibrium chamber was immersed in a constant temperature oil bath and the total pressure imposed upon the system by a cylinder of carbon dioxide attached downstream to the condenser.

The vapor stream to be supplied to the equilibrium chamber originated as a C<sub>4</sub> hydrocarbon liquid consisting of isobutane, 1-butene, or mixtures of the two. This liquid was heated in a closed tank to build up sufficient pressure to force a stream of the liquid through a control valve to a flash vaporizer. The resulting stream of hydrocarbon gas next bubbled through two chambers containing liquid water held in a bath at a controlled temperature. By controlling the temperature of this bath the amount of water vaporized into the gas stream could be adjusted. At lower temperatures and pressures, the gas stream approached saturation with respect to water vapor after passing through the water saturation chambers; at more extreme conditions, saturation efficiency fell off to around 50%. The gas mixture of C<sub>4</sub> hydrocarbons and water was passed next

<sup>†</sup> Additional matter, namely, Tables 3-6, 10, and 11 are on file (Document 3035) with the American Documentation Institute, 1719 N Street, N.W., Washington, D.C. Copies can be obtained by remitting \$1.00 for microfilm or \$1.00 for photocopies.

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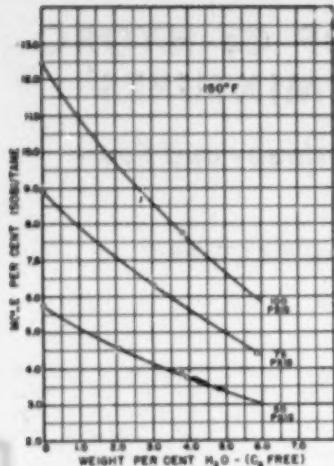


Fig. 1. Solubility of isobutane in furfural-water mixtures at 150°F. Water concentration in the ternary liquid is expressed as wt.% on an isobutane-free basis. Parameter is total pressure expressed as lb./sq.in. gage.

through heated lines to a chamber containing furfural held at the same temperature as the equilibrium chamber. In this chamber the gas picked up furfural vapor and was brought to the temperature of the equilibrium chamber. The constant composition, constant temperature gas stream next passed through the equilibrium chamber, was condensed, and collected. The fur-

fural saturation chamber eventually reached a composition approaching closely that of the equilibrium chamber, and both chambers were charged with liquid of composition about equal to the final equilibrium value to lessen the time required for each run.

After attainment of equilibrium conditions, duplicate samples of vapor and liquid were taken according to methods previously described (2). In the quaternary runs, vapor samples were analyzed for the relative isobutane to 1-butene content by absorption of the unsatrate in mercuric nitrate-catalyzed silver nitrate solution (2). A separate vapor sample was withdrawn for water content determination by passing a known amount of vapor over calcium chloride drying tubes. Selectivity of the calcium chloride for water vapor alone was shown through tests made with pure hydrocarbon gases, and by the fact that at low gas rates the partial pressure of water in the vapor was found equal to the vapor pressure of liquid water in the water saturator chambers. Samples of the liquid were analyzed in the same manner as described by Gerster et al. (2). In their method carbon dioxide gas was employed to strip the  $C_4$  hydrocarbon gases from the weighed sample bomb. The resulting gas mixture passed through a calcium chloride drying tower to remove the water vapor, after which the carbon dioxide gas was absorbed in a caustic solution. The volume of  $C_4$  hydrocarbon gas remaining was measured, after which, in the quaternary runs, the quantity of 1-butene present was determined by absorption in the same mercuric nitrate-silver nitrate solution. Separate liquid samples were withdrawn for water analysis. These weighed samples were vented to the atmosphere after cooling to 32°F. to allow the  $C_4$  hydrocarbon gases slowly to escape. The remaining

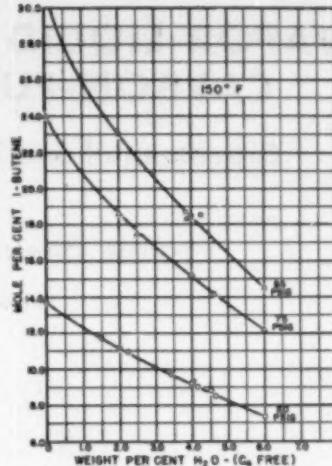


Fig. 2. Solubility of 1-butene in furfural-water mixtures at 150°F. Water concentration in the ternary liquid is expressed as wt.% on a 1-butene-free basis. Parameter is total pressure expressed as lb./sq.in. gage.

furfural-water mixture was analyzed by a cloud point method (3).

### Experimental Results—Ternary Systems

*Isobutane-Water-Furfural and 1-Butene-Water-Furfural.* Solubilities of isobutane and 1-butene were determined separately in furfural-water solutions containing up to 6 wt. or 25.4 mole % water. Determinations were made at temperatures of 100°, 150°, and 200°F., and at each of these temperatures runs were made at various constant total pressure values with water con-

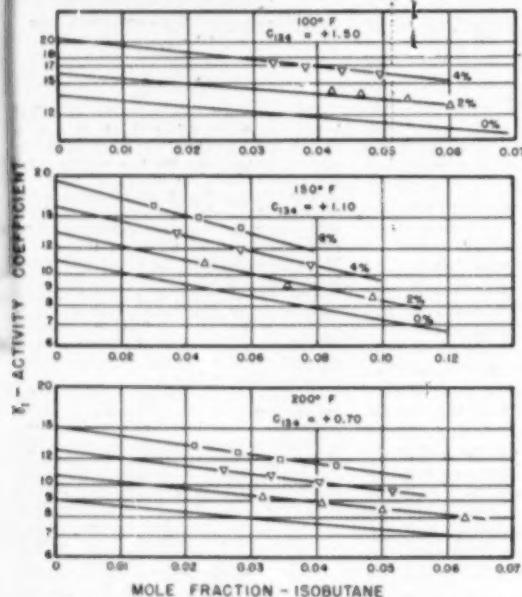


Fig. 3. Activity coefficient values for isobutane present in mixtures with furfural and water at 100°, 150°, and 200°F., as a function of isobutane concentration in the ternary liquid. Parameter is water concentration in the ternary liquid expressed as wt. % on an isobutane-free basis. Points represent values computed from smoothed solubility data such as Fig. 1. Lines represent values predicted by Eq. (2).

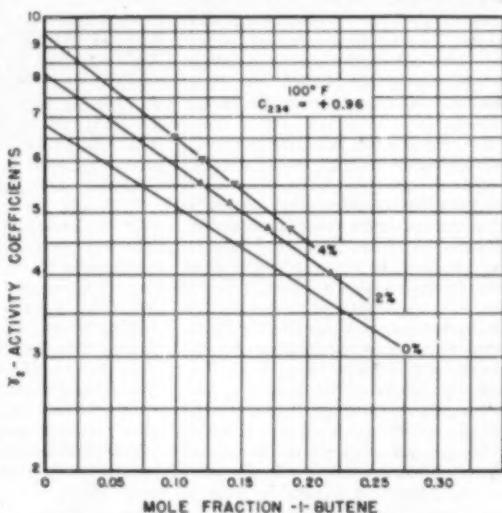


Fig. 4a. Activity coefficient values for 1-butene present in mixtures with furfural and water at 100°F. as a function of 1-butene concentration in the ternary liquid. Parameter is water concentration in the ternary liquid expressed as wt. % on a 1-butene-free basis. Points represent values computed from smoothed solubility data such as Fig. 2. Lines represent values predicted by Eq. (2).

TABLE 1 VAPOR PRESSURES OF ISOBUTANE, 1-BUTENE, WATER, AND FURFURAL AT VARIOUS TEMPERATURES

Temp. °F.	Vapor Pressures, mm. Hg			
	Isobutane	1-Butene	Water	Furfural
100	3720	3232	49.1	4.7
150	7399	6511	192.0	22.2
200	13,256	11,790	596.0	76.8

tent as the main variable. Constant pressure rather than constant water-furfural ratio in the liquid was chosen as the second parameter since the water content of the gas stream entering the equilibrium chamber could not be adjusted too easily to an exact desired value.

Results are plotted in Figures 1 and 2 for isobutane and 1-butene at 150° F. These plots show the liquid solubility of isobutane or 1-butene as a function of the water-furfural ratio of the liquid at various total pressures up to 100 lb./sq.in. gage. Previous data were available for C<sub>4</sub> hydrocarbon solubilities in dry furfural (9) and these data provided points at 0% water. Smooth curves resulted which showed that as the water content of the liquid increased, the solubility of each C<sub>4</sub> hydrocarbon decreased quite rapidly. At any constant water-furfural ratio in the liquid, the solubility of each C<sub>4</sub> hydrocarbon in the liquid phase increased with total pressure.

Activity coefficient values were computed for each of the C<sub>4</sub> hydrocarbons out of wet furfural from the relationship

$$\gamma_i = \frac{x_i P_i}{P_i x_i} \quad (1)$$

These values were calculated at three different water-furfural ratios in the liquid for convenience in presenting and correlating the results in terms of the other main variables of C<sub>4</sub> hydrocarbon composition and temperature. The water-furfural ratios chosen for this calculation corresponded to 2, 4, and 6 wt. % water in the furfural computed on a C<sub>4</sub> hydrocarbon-free basis. Values of x<sub>i</sub> at these water concentrations were taken from solubility plots such as Figures 1 and 2. Values of the correction term, z<sub>ii</sub>, which takes into account the non-idealities of the gas and effect of pressure on the liquid, were estimated in the same manner as previously described (9). Vapor-pressure values for the C<sub>4</sub> hydrocarbons (6), water (8), and furfural (10) have been given for convenience in Table 1. Values of P<sub>v</sub>, the partial pressure of the C<sub>4</sub> hydrocarbon in the gas phase, were not directly measured by analysis but were computed by subtracting the partial pressure of furfural and water in the vapor from the measured total pressure. Values of partial pressure of furfural in the vapor phase were readily estimated assuming the furfural activity coefficient to be unity. Since the vapor pressure of furfural is less than 1% of the total pressures employed, such an assumption does not introduce error to the value of the C<sub>4</sub> hydrocarbon partial pressure to any extent. The amount of water in the vapor phase was estimated using the data of Pearce and Gerster (10) who measured experimental vapor-liquid relationships in the furfural-water system. Addition of C<sub>4</sub> hydrocarbons to the furfural-water liquid causes a small increase in the volatility of the water according to data of Griswold et al. (5) for C<sub>4</sub> hydrocarbon-water-furfural mixtures at the two-phase point. This small change in the volatility of the water in the presence of C<sub>4</sub> hydrocarbon was not great enough to affect markedly the activity coefficient results for either of the two C<sub>4</sub> hydrocarbons, since the partial pressure values of the water were small compared to those for the C<sub>4</sub>

TABLE 2 PARTIAL PRESSURE OF WATER VAPOR FROM WATER-FURFURAL SOLUTIONS (10)

Temp. °F.	Partial Pressure, mm. Hg		
	2 Wt.-% Water	4 Wt.-% Water	6 Wt.-% Water
100	35	44	--
150	105	145	173
200	248	353	387

hydrocarbons. The water partial-pressure values were therefore assumed to be the same regardless of the C<sub>4</sub> hydrocarbon concentration, and are given in Table 2, as computed from the data of Pearce and Gerster (10).

The resulting activity coefficients are plotted in Figures 3 and 4 as a function of the C<sub>4</sub> hydrocarbon concentration in the liquid and the water concentration in the liquid. These results show that as the water content of the liquid is increased, the activity coefficients for the C<sub>4</sub> hydrocarbons are also increased, and that at any constant water-furfural ratio in the liquid, activity coefficients decrease with increasing temperature and increasing C<sub>4</sub> hydrocarbon concentration.

Heats of solution were computed for isobutane or 1-butene with furfural-water mixtures using the same methods previously employed (9). Results are given in Table 7 where it may be seen that the heat of solution values are essentially independent of the water concentration of the system, at least within the concentration range studied.

### Application of Equations to Results

**Ternary Mixtures.** As mentioned previously, the systems isobutane-water-furfural and 1-butene-water-furfural were determined experimentally to provide a basis for the later quaternary data involving mixtures of these four components. Before extending the theoretical treatment to the quaternary data, application of the three-suffix Margules ternary equations was made to these ternary data to test their validity when applied to such extremely non-ideal solutions, and to determine the ternary constants needed for the later quaternary calculations.

The three-suffix Margules ternary equations are given below in the form proposed by Wohl (12). In the later quaternary sections, subscripts are assigned which increase with the boiling

point of each of the four components; that is, isobutane is component 1, 1-butene is component 2, water is component 3, and furfural is component 4. To minimize confusion, the same subscript notation is used here, and the three-suffix Margules ternary equation for isobutane-water-furfural mixtures is written in terms of subscripts 1, 3, and 4 as follows:

$$\log \gamma_1 = x_3^2 [A_{1-3} + 2x_1(A_{3-1} - A_{1-3})] + x_3^2 [A_{1-4} + 2x_1(A_{4-1} - A_{1-4})] + x_3 x_4 [A_{3-1} + A_{1-4} - A_{3-4}] + 2x_1(A_{4-1} - A_{3-4}) + 2x_4(A_{1-3} - A_{3-4}) - (1 - x_1)C_{131} \quad (2)$$

The corresponding equation for the 1-butene-water-furfural system may be obtained by substituting subscript 2 for subscript 1 throughout. These equations are seen to express the ternary activity coefficients for each C<sub>4</sub> hydrocarbon,  $\gamma_1$  or  $\gamma_2$ , according to the liquid composition in terms of mole fraction,  $x$ , six binary constants expressed as  $A_{ij}$ , and one ternary constant,  $C$ . Two binary constants are required to define each of the three binary pairs which make up the ternary system, and each binary constant is directly obtainable from the binary equilibrium data since it is defined as the logarithm of the activity coefficient of one of the binary components as the concentration of that component in the liquid approaches zero.

To apply Equation (2) to the isobutane-furfural and 1-butene-furfural systems, experimental data for the following binary systems should be known: isobutane-water, 1-butene-water, isobutane-furfural, 1-butene-furfural, and water-furfural. Information for the latter three binary systems are

TABLE 7 HEATS ABSORBED ON SOLUTION OF LIQUID ISOBUTANE OR 1-BUTENE IN FURFURAL-WATER SOLUTIONS CONTAINING FROM 2-6 WEIGHT PERCENT WATER (C<sub>4</sub> HYDROCARBON-FREE) OVER RANGE 100° TO 200° F.

Compn. Mole % C <sub>4</sub>	Isobutane		1-Butene	
	Differential Heats of Soln., 100-200° F., B.t.u./lb. Mole of C <sub>4</sub> Dissolved	Integral Heats of Soln., 100-200° F., B.t.u./lb. Mole of C <sub>4</sub> Dissolved	Differential Heats of Soln., 100-200° F., B.t.u./lb. Mole of C <sub>4</sub> Dissolved	Integral Heats of Soln., 100-200° F., B.t.u./lb. Mole of C <sub>4</sub> Dissolved
0	3750	2400	3750	2400
5	3530	--	3620	--
10	3290	1920	3500	2160
20	--	1470	--	1920
0	3750	2400	3750	2400
5	3620	--	3620	--
10	3500	2160	3500	2160
20	--	1920	--	1920

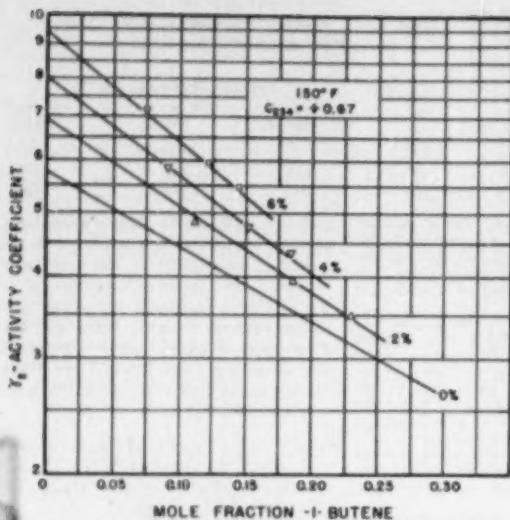


Fig. 4b. Activity coefficient values for 1-butene present in mixtures with furfural and water at 150° F. as a function of 1-butene concentration in the ternary liquid. Parameter is water concentration in the ternary liquid expressed at wt. % on a 1-butene-free basis. Points represent values computed from smoothed solubility data such as Fig. 2. Lines represent values predicted by Eq. (2).

accurately known (9, 10), while some literature data are available on the solubility of water and  $C_4$  hydrocarbons. Katz and McKetta (7) reported vapor-liquid equilibrium data for the methane-butane-water system from which estimates of the solubility of  $n$ -butane in water were made. In the absence of specific information in the literature for the solubility of isobutane or 1-butene

in water, these data were determined experimentally by passing the pure  $C_4$  hydrocarbon gases through the water saturator chamber of the equilibrium apparatus. Activity coefficients were computed from Equation 1, assuming the partial pressure of water in the vapor phase was equal to the vapor pressure of water. Because of the extremely low solubilities obtained, the computed activity coefficients were assumed to be the values at infinite dilution. The resulting binary constants are given in Table 8 at temperatures of 100°, 150°, and 200° F. The binary constants for  $n$ -butane-water computed from the Katz and McKetta data were intermediate in value between those determined experimentally for isobutane and 1-butene. Data for the solubility of water in various  $C_4$  hydrocarbons have been summarized by Griswold, Klecka, and West (4) from which activity coefficients and binary constants were computed as above at the temperatures of 100°, 150°, and 200° F. These values are also given in Table 8.

Values to be used for the binary constants to describe the water-furfural system were somewhat in doubt since Pearce and Gerster showed that it was not possible to fit their data for this system over the complete concentration range with a three-suffix Margules equation (10). Actually in the present case where the main interest lies with the  $C_4$  hydrocarbon activity coefficients, the water-furfural binary constants do not contribute to a great degree to the prediction of these values. When the

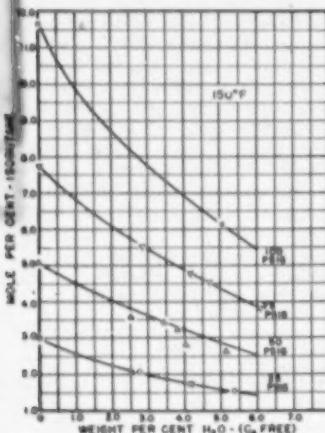


Fig. 5. Solubility of Isobutane in 1-butene - water - furfural mixtures at 150° F. Vapor concentration is 82.2 mole per cent isobutane and 17.8 mole per cent 1-butene on a water-free and furfural-free basis. Water concentration in the quaternary liquid is expressed as wt. % on a  $C_4$  hydrocarbon-free basis. Parameter is total pressure expressed as lb./sq.in. gage.

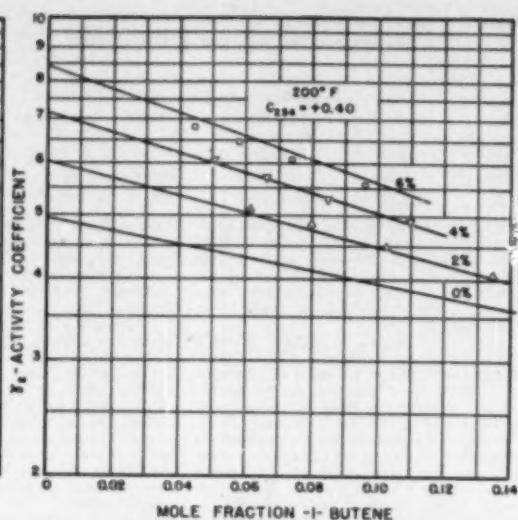


Fig. 4c. Activity coefficient values for 1-butene present in mixtures with furfural and water at 200° F. as a function of 1-butene concentration in the ternary liquid. Parameter is water concentration in the ternary liquid expressed at wt. % on a 1-butene-free basis. Points represent values computed from smoothed solubility data such as Fig. 2. Lines represent values predicted by Eq. (2).

water-furfural binary constants employed in the ternary equations were taken as the experimental end values of  $\log \gamma$  for each component, a satisfactory agreement was obtained as will be shown later between actual values of the  $C_4$  hydrocarbon activity coefficients and those predicted by the ternary equations. Pearce and Gerster did show that their water-furfural binary data could be fitted with a three-suffix Mar-

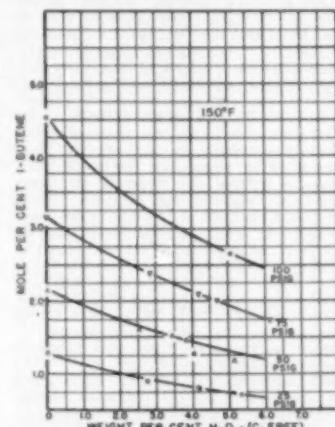


Fig. 6. Solubility of 1-butene in isobutane-water-furfural mixtures at 150° F. Vapor concentration is 82.2 mole per cent isobutane and 17.8 mole per cent 1-butene on a water-free and furfural-free basis. Water concentration in the quaternary liquid is expressed as wt. % on a  $C_4$  hydrocarbon-free basis. Parameter is total pressure expressed as lb./sq.in. gage.

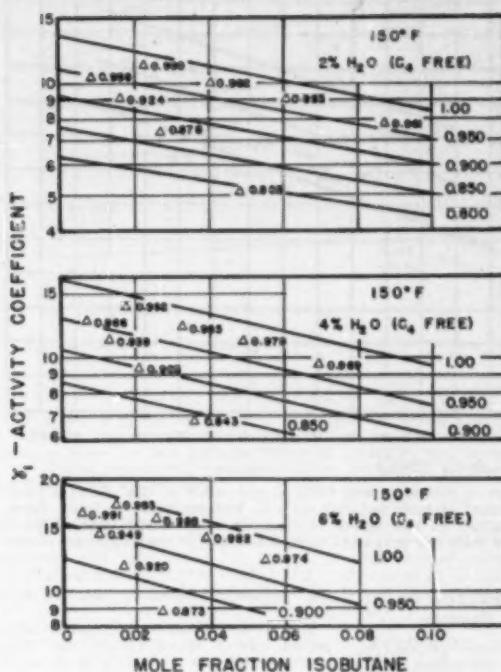


Fig. 7. Activity coefficient values for isobutane present in mixtures with 1-butene, furfural, and water at 150° F. as a function of isobutane concentration in the quaternary liquid. Separate plots are given for 2, 4, and 6 wt. % water in the quaternary liquid computed on a C<sub>4</sub> hydrocarbon-free basis. Points represent values computed from smoothed solubility data such as Fig. 5. Lines represent values predicted by Eq. (3). Parameter numbers on graph are values of  $(x_0 + x_1)/(x_0 + x_1 + x_3)$ .

gules equation provided that only the high furfural concentration range were considered and that the binary constant corresponding to the end value in the high water concentration range were arbitrarily adjusted until a good fit was obtained. Use of this adjusted binary constant was alternatively made in the ternary equations since the ternary data were completely in the high furfural concentration range. The resulting fit between experimental and predicted C<sub>4</sub> hydrocarbon ternary activity coefficients was equally good as that obtained previously. This illustrates an important and valuable property of these ternary equations: namely, that binary constants describing concentration ranges which are not of interest in the ternary predictor need not be known with a great deal of accuracy. If activity coefficient values for the water and furfural components of the present ternary systems were of great interest, use of the arbitrarily adjusted binary constant would be recommended for the concentration range wherein it applies. For the present case, the experimental end values

of  $\log \gamma$  appear adequate for the water-furfural binary constants. These values are tabulated in Table 8, and were used in all subsequent calculations.

Values of the binary constants to

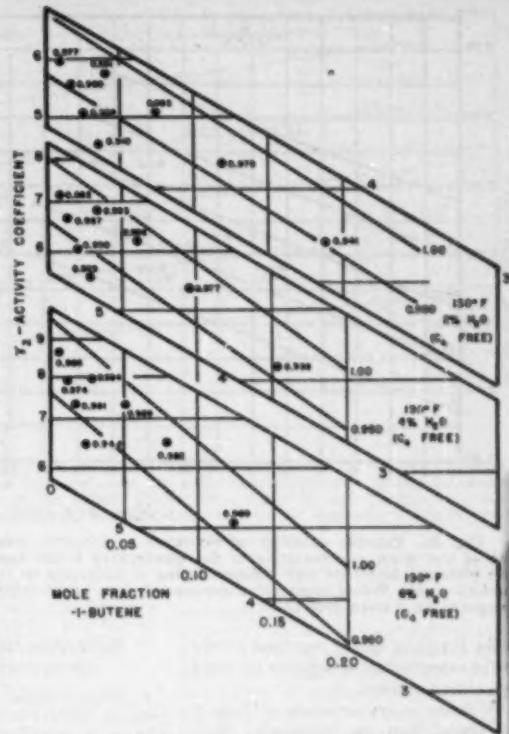


Fig. 8. Activity coefficient values for 1-butene present in mixtures with isobutane, furfural, and water at 150° F. as a function of 1-butene concentration in the quaternary liquid. Separate plots are given for 2, 4, and 6 wt. % water in the quaternary liquid computed on a C<sub>4</sub> hydrocarbon-free basis. Points represent values computed from smoothed solubility data such as Fig. 6. Lines represent values predicted by Eq. (3). Parameter numbers on graph are values of  $(x_0 + x_1)/(x_0 + x_1 + x_3)$ .

describe the isobutane-furfural and 1-butene-furfural systems were taken from the paper of Mertes and Colburn (9) and are also given in Table 8. These constants are used with the three

TABLE 8  
VALUES OF BINARY CONSTANTS FOR USE  
IN THREE-SUFFIX MANIFOLD EQUATIONS

Binary System	100° F.	150° F.	200° F.
Isobutane - 1-Butene			
$A_{1-2}$	0	0	0
$A_{2-1}$	0	0	0
Isobutane - Water			
$A_{1-3}$	4.35	4.04	3.78
$A_{3-1}$	3.90	2.78	2.20
1-Butene - Water			
$A_{2-3}$	3.58	3.52	3.46
$A_{3-2}$	2.53	2.08	1.69
Isobutane - Furfural			
$A_{1-4}$	1.142	1.042	0.955
$A_{4-1}$	1.310	1.160	1.030
1-Butene - Furfural			
$A_{2-4}$	0.842	0.763	0.700
$A_{4-2}$	1.029	0.951	0.900
Water - Furfural			
$A_{3-4}$	1.072	0.909	0.780
$A_{4-3}$	2.114	1.945	1.748

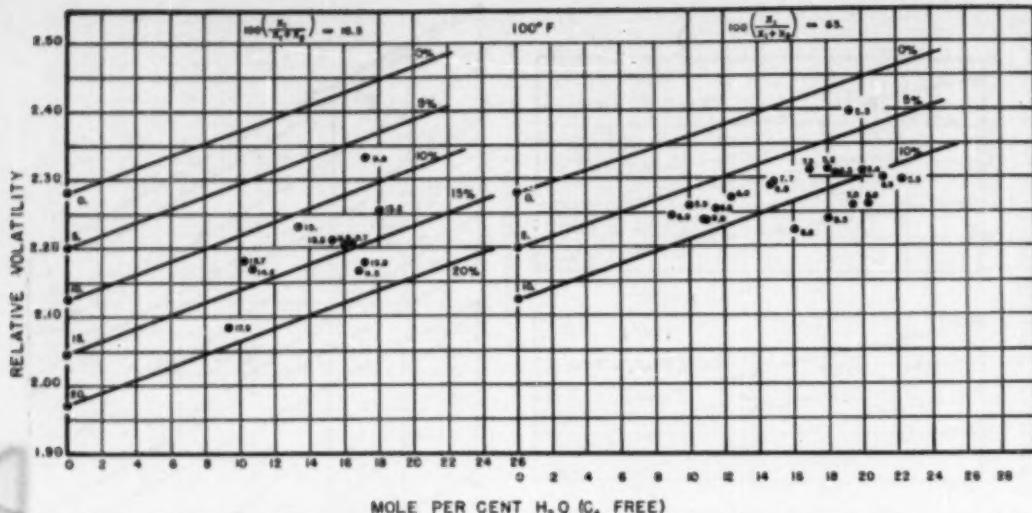


Fig. 9a. Relative volatility of isobutane to 1-butene present in mixtures with furfural and water at 100° F. as a function of the water concentration in the quaternary liquid expressed as mole per cent on a C<sub>4</sub> hydrocarbon-free basis. Separate plots are given for two different ratios of isobutane to 1-butene in the liquid: (100x<sub>1</sub>)/(x<sub>1</sub> + x<sub>2</sub>) = 16.5 and (100x<sub>1</sub>)/(x<sub>1</sub> + x<sub>2</sub>) = 65. Points represent experimental data. Parameter is mole per cent total C<sub>4</sub> hydrocarbon in the quaternary liquid computed on a water-free basis.

suffix Margules binary equations closely fit the experimental data points for these two binary systems.

With the binary constants of Table 8 substituted into the three-suffix Margules ternary equations given above as Equation (2), good agreement between predicted and experimental activity coefficient values was obtained after a suitable ternary constant *C* was introduced. This is shown in Figures 3, 4a, 4b, and 4c where experimental activity coefficients for the C<sub>4</sub> hydrocarbon present in the furfural-water mixtures are compared with values predicted by the equations. The best values of *C* were chosen by trial and found to lie within the range of 0.4 to 1.5 as shown in Table 9. These values were larger than the values around -0.2 found applicable for ternary mixtures consisting of two C<sub>4</sub> hydrocarbons and furfural (2). This might be expected because of the extreme nonideality of the C<sub>4</sub> hydrocarbon-water binary pairs.

### Experimental Results for Quaternary System

**Isobutane-1-Butene-Water-Furfural.** The solubility of mixtures of isobutane and 1-butene in water-furfural was determined under the same operating conditions as for the previous case where only a single C<sub>4</sub> hydrocarbon was present. Temperatures of 100°, 150°, and 200° F., water concentrations up to 6 wt. % in the C<sub>4</sub> hydrocarbon-free liquid, and total pressures up to 100 lb./sq.in. gage were investigated. In addition, two different ratios of isobutane to 1-butene in the gas phase were studied for all conditions. These ratios were 4.62 and 0.425, moles of isobutane to moles of 1-butene. Since the vapor for the equilibrium still was generated externally, it was simpler experimentally to maintain the C<sub>4</sub> hydrocarbon ratio nearly constant in the gas phase than in the liquid.

Typical plots of the results are shown in Figures 5 and 6, where the solubility of each C<sub>4</sub> hydrocarbon component in the liquid is shown at 150° F. and at a C<sub>4</sub> hydrocarbon vapor ratio of 4.62 moles of isobutane to one mole of 1-butene as a function of the water-furfural ratio in the liquid and at various total pressures. Values plotted for zero water content were taken from previously reported data for

the isobutane-1-butene-furfural system (2).

Activity coefficients were computed from smooth curves drawn through the data points of each plot at even values of water content in the liquid of 2, 4, and 6 wt. % computed on a C<sub>4</sub> hydrocarbon-free basis. The activity coefficients were calculated from Equation (1), estimating as before the values of *a*, the nonideality correction term for the gas phase and effect of pressure on the liquid. Values of the partial pressures of furfural and water in the vapor were also estimated as before.

The activity coefficient values for each C<sub>4</sub> hydrocarbon component are plotted in Figures 7 and 8 for 150° F. only as a function of the component composition in the liquid. Separate plots are given for each C<sub>4</sub> component and for each water concentration in the liquid. The parameter for each of the isobutane plots is the function  $(x_1 + x_2)/(x_3 + x_4 + x_5)$ , where  $x_1$ ,  $x_2$ , and  $x_3$  refer to the mole fraction of 1-butene, water, and furfural, respectively, in the liquid. This parameter is inversely proportional to the amount of 1-butene present in the water-furfural solvent. As the parameter value approaches unity, the 1-butene concentration approaches zero and the ternary system isobutane-water-furfural results. Similarly, as the isobutane concentration approaches zero, the ternary system 1-butene-water-furfural results. A similar method was employed for plotting the 1-butene quaternary activity coefficients.

Inspection of Figures 7-8 shows that the activity coefficient values for each C<sub>4</sub> hydrocarbon component decrease with increasing amounts of that component in the liquid, and also decrease with increasing amounts of the other C<sub>4</sub> hydrocarbon component in the liquid. The lowering of each C<sub>4</sub> hydrocarbon activity coefficient is nearly the same regardless of which C<sub>4</sub> component increases in amount. For example, consider three cases from Figure 7 each with the same total amount of C<sub>4</sub> hydrocarbon present in the liquid. When the liquid composition is 0.04 mole fraction isobutane and 0.048 mole fraction 1-butene (corresponding to a parameter value of 0.95), the

TABLE 9  
VALUES OF TERNARY CONSTANTS FOR USE  
IN THREE-SUFFIX MARGULES EQUATIONS

Ternary System	100° F.	150° F.	200° F.
Isobutane - 1-Butene - Water			
C <sub>123</sub>	1.0	1.1	1.2
Isobutane - 1-Butene - Furfural			
C <sub>124</sub>	-0.20	-0.18	-0.17
Isobutane - Water - Furfural			
C <sub>134</sub>	1.5	1.1	0.7
1-Butene - Water - Furfural			
C <sub>234</sub>	0.96	0.67	0.40

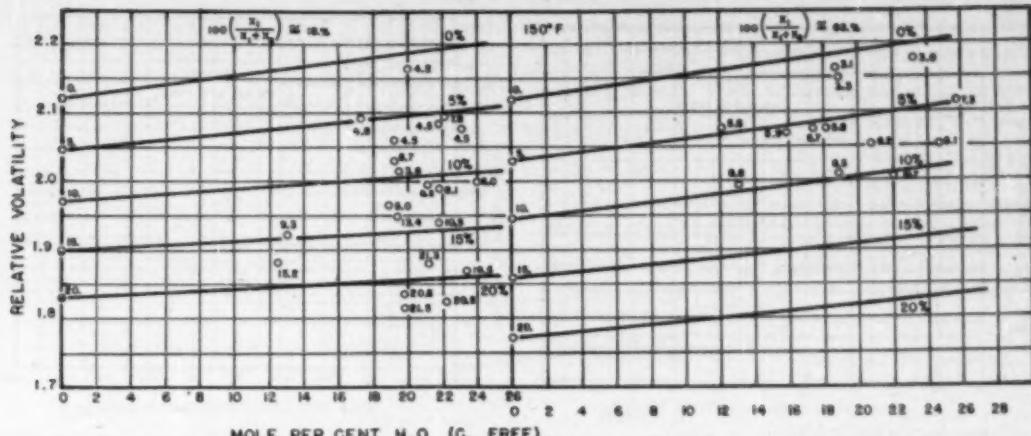


Fig. 9b. Relative volatility of isobutane to 1-butene present in mixtures with furfural and water at 150° F. as a function of the water concentration in the quaternary liquid expressed as mole per cent on a C<sub>4</sub> hydrocarbon-free basis. Separate plots are given for two different ratios of isobutane to 1-butene in the liquid: (100x<sub>1</sub>)/(x<sub>1</sub> + x<sub>2</sub>) = 18 and (100x<sub>1</sub>)/(x<sub>1</sub> + x<sub>2</sub>) = 68. Points represent experimental data. Parameter is mole per cent total C<sub>4</sub> hydrocarbon in the quaternary liquid computed on a water-free basis.

activity coefficient for isobutane,  $\gamma_1$ , is 10.3; when the composition is 0.088 mole fraction isobutane with only traces of 1-butene (corresponding to a parameter value of 1.0),  $\gamma_1$  is 10.1; and when the composition is 0.088 mole fraction 1-butene with only traces of isobutane (corresponding to a parameter value of 0.91),  $\gamma_1$  is 11.0. These differences are not great, although for precise work, could probably not be neglected. It is also of interest to note that in the present case where C<sub>4</sub> hydrocarbon activity coefficients are not greatly affected by the relative amounts of each C<sub>4</sub> component but mainly by the total amount of C<sub>4</sub> hydrocarbon present, correlation of results is simplified by use of the parameter

$\frac{x_1 + x_2}{x_1}$  for plots such as Figure 7.

Experimental results have been computed also in terms of the relative volatility of isobutane to 1-butene and are plotted in Figures 9-12.

#### Application of Equations for Prediction of Activity Coefficients

**Results for the Quaternary System.** Although little prior literature exists reporting measurements of vapor-liquid equilibrium data for nonideal quaternary systems, many types of general multi-

component equations have been proposed to relate the equilibrium properties of such systems. Benedict, Johnson, and Rubin (1), Wohl (12), and Redlich and Kister (11) all present equations derived from considerations of the excess free energy of mixing. All assumed an empirical power-series expression for the excess free energy of mixing. Benedict et al. regarded their power series as a problem in curve fitting. The constants of their equations must be evaluated directly from experimental data of the multicomponent system considered.

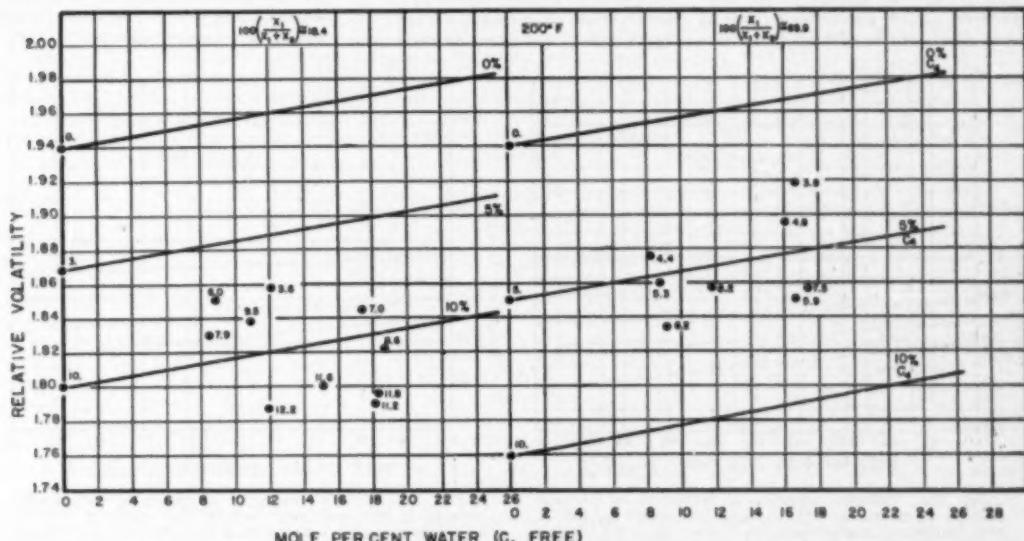


Fig. 9c. Relative volatility of isobutane to 1-butene present in mixtures with furfural and water at 200° F. as a function of the water concentration in the quaternary liquid expressed as mole per cent on a C<sub>4</sub> hydrocarbon-free basis. Separate plots are given for two different ratios of isobutane to 1-butene in the liquid: (100x<sub>1</sub>)/(x<sub>1</sub> + x<sub>2</sub>) = 18 and (100x<sub>1</sub>)/(x<sub>1</sub> + x<sub>2</sub>) = 70. Points represent experimental data. Parameter is mole per cent total C<sub>4</sub> hydrocarbon in the quaternary liquid computed on a water-free basis.

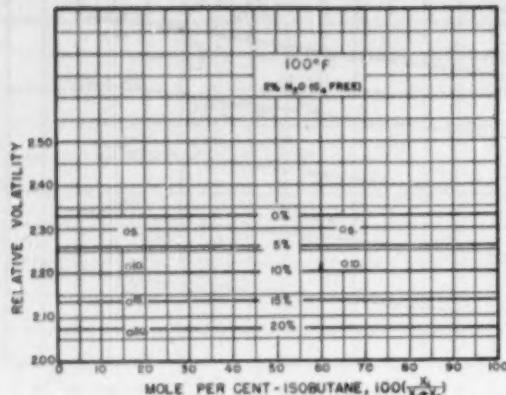


Fig. 10a. Relative volatility of isobutane to 1-butene present in mixtures with furfural and water at 100° F. as a function of the composition  $(100x_1)/(x_1 + x_2)$ . Water concentration in the quaternary liquid is 2 wt. per cent computed on a C<sub>1</sub> hydrocarbon-free basis. Parameter values are mole per cent total C<sub>1</sub> hydrocarbon in the quaternary liquid computed on a water-free basis. Points are from best lines through experimental data from Fig. 9a. Solid lines are predicted from Eq. (7).

There is no simple relationship between their constants and the constants for the subsystems with a smaller number of components. Wohl gave the equations such a form that the constants for a system composed of several components can be determined—either completely or partly, according to the number of power terms employed—from measurements on the subsystems with a smaller number of components. Equations for the excess free energy are symmetrical with respect to the mole fractions. These equations as well as those which can be derived from them

contain the higher power terms as corrections of the terms of lower power. This representation offers the advantage of a natural classification of the various systems. The lowest power terms used in these equations have the significance of end values of the logarithms of the activity coefficients for an infinitely dilute solution. As these quantities, multiplied with RT, are equal to the difference of the free energies of the two standard states (the hypothetical pure state as extrapolated from the infinitely dilute solution and the real pure liquid state), the choice of these con-

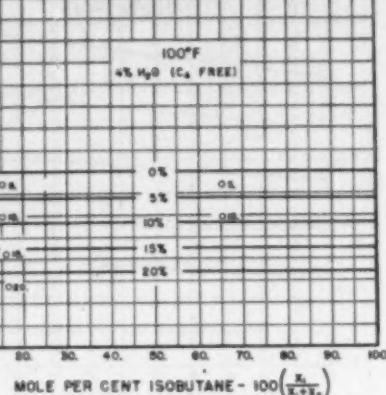


Fig. 10b. Relative volatility of isobutane to 1-butene present in mixtures with furfural and water at 100° F. as a function of the composition  $(100x_1)/(x_1 + x_2)$ . Water concentration in the quaternary liquid is 4 wt. per cent computed on a C<sub>1</sub> hydrocarbon-free basis. Parameter values are mole per cent total C<sub>1</sub> hydrocarbon in the quaternary liquid computed on a water-free basis. Points are from best lines through experimental data from Fig. 9a. Solid lines are predicted from Eq. (7).

stants is thermodynamically advantageous in many respects. Redlich and Kister have presented similar equations in which no use is made of the end values of the logarithms of the activity coefficients.

The three-suffix Margules equations as derived by Wohl were chosen for testing the present quaternary data since this equation type was found applicable to the important binary and ternary systems from which the present quaternary system is composed. These equations are given below for the activ-

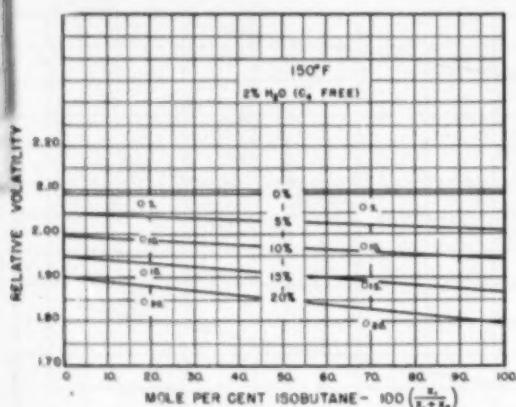


Fig. 11a. Relative volatility of isobutane to 1-butene present in mixtures with furfural and water at 150° F. as a function of the composition  $(100x_1)/(x_1 + x_2)$ . Water concentration in the quaternary liquid is 2 wt. per cent computed on a C<sub>1</sub> hydrocarbon in the quaternary liquid computed on a water-free basis. Points are from best lines through experimental data from Fig. 9b. Solid lines are predicted from Eq. (7).

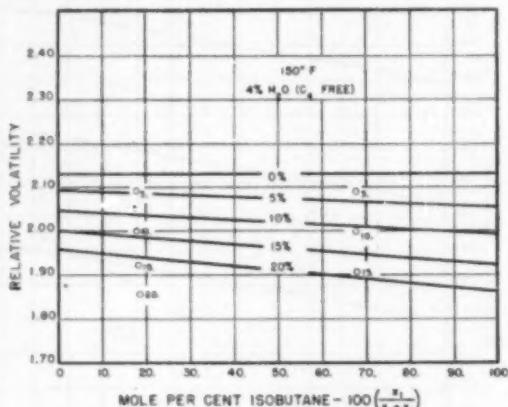


Fig. 11b. Relative volatility of isobutane to 1-butene present in mixtures with furfural and water at 150° F. as a function of the composition  $(100x_1)/(x_1 + x_2)$ . Water concentration in the quaternary liquid is 4 wt. % computed on a C<sub>1</sub> hydrocarbon-free basis. Parameter values are mole per cent total C<sub>1</sub> hydrocarbon in the quaternary liquid computed on a water-free basis. Points are from best lines through experimental data from Fig. 9b. Solid lines are predicted from Eq. (7).

ity coefficient for component 1 present in a quaternary mixture:

$$\begin{aligned} \log \gamma_1 = & x_2^2[A_{1-2} + 2x_1(A_{2-1} - A_{1-2})] \\ & + x_3^2[A_{1-3} + 2x_1(A_{3-1} - A_{1-3})] \\ & + x_4^2[A_{1-4} + 2x_1(A_{4-1} - A_{1-4})] \\ & + x_2x_3[A_{2-3} + A_{1-3} - A_{3-2}] \\ & + 2x_1(A_{3-1} - A_{1-3}) \\ & + 2x_3(A_{3-2} - A_{2-3}) \\ & - (1 - 2x_1)C_{123} + x_2x_4[A_{2-1} \\ & + A_{1-4} - A_{4-2}] \\ & + 2x_1(A_{4-1} - A_{1-4}) \\ & + 2x_4(A_{4-2} - A_{2-4}) \\ & - (1 - 2x_1)C_{124} \\ & + x_3x_4[A_{3-1} + A_{1-4} - A_{4-3}] \\ & + 2x_1(A_{4-1} - A_{1-4}) \\ & + 2x_4(A_{4-3} - A_{3-4}) \\ & - (1 - 2x_1)C_{134} + x_2x_3x_4[A_{4-2} \\ & - A_{2-4} + C_{234}]. \end{aligned} \quad (3)$$

This equation contains 12 binary constants and 4 ternary constants, and has no quaternary constant. The binary constants are the same as those required to describe each of the six binary mixtures from which the quaternary system is composed, while the ternary constants are the same as those from the ternary three-suffix Margules equations when applied to each of the four ternary mixtures from which the quaternary system is composed. Quaternary and higher constants do not occur as long as one does not pass over to four-suffix equations.

The corresponding quaternary equation for predicting the activity coefficients of component 2 may be derived from Equation (3) by substituting subscript 2 for 1, 3 for 2, 4 for 3, and 1 for 4. This cyclic permutation may be repeated to obtain equations for the other components. It is also of interest to note that these quaternary equations pass over to the corresponding ternary equations by omitting all terms containing the subscript referring to the component omitted; they also pass over to the corresponding binary equations by omitting all terms containing the subscripts of the two components omitted.

Use of Equation (3) to predict and extend the quaternary data requires knowledge of the same six binary mixtures which go to make up the previously reported ternary mixtures isobutane-1-butene-furfural, isobutane-water-furfural, and 1-butene-water-furfural. Since the binary constants previously chosen were satisfactory for predicting results of these three ternary mixtures, it may be assumed that they are of sufficient precision for application to the quaternary mixture. Ternary constants were also determined experimentally for each of these ternary systems, but no experimental data are available for the fourth ternary mixture, isobutane-1-butene-water. Often one or more of the ternary systems will not be well known in prediction of quaternary data, in which case the ternary system

may be estimated from knowledge of the three binary pairs making up the ternary system through use of the three-suffix Margules ternary equations assuming the ternary effect is negligible. Wohl has shown that for such a case, rather than assume that the ternary constant is zero, it is more desirable to assume the following:

$$\begin{aligned} C_{123} = & 1/2[(A_{2-1} - A_{1-2}) \\ & + (A_{1-3} - A_{2-3}) \\ & + (A_{3-2} - A_{2-3})] \end{aligned} \quad (4)$$

Such an assumption was not valid for the present case, in that a fairly large value of the ternary constant  $C_{123}$  was required for optimum fitting of the data with the equations. Evaluation of this constant was made from the quaternary relative volatility data, and a discussion of this procedure is given later.

The final agreement between predicted and experimental quaternary activity coefficients is shown in Figures 7 and 8. These plots show that on the whole the equations give a satisfactory representation of the data and could be used with confidence for extending the present data or predicting other quaternary data from basic binary and some ternary data. It is recognized that the range of composition covered by the present quaternary system has been limited because of miscibility considerations, and any generalizations regarding the use of the theoretical equations for other systems must therefore also be limited. Use of these equations for general design purposes with  $C_4$  hydrocarbon-water-furfural systems appears very promising. Additional experimental data for several other  $C_4$  hydrocarbons with furfural and furfural-water solvents are currently being determined in these laboratories, and will be reported in a subsequent paper.

### Quaternary Results as Relative Volatility

Expression of the quaternary results in terms of the relative volatility of isobutane to 1-butene in the presence of the furfural-water solvent is often more desirable for distillation applications. Values of relative volatility were computed directly from experimental data by the equation

$$\alpha_{12} = (y_1 x_2) / (x_1 y_2) \quad (5)$$

Values of relative volatility may be expressed in terms of activity coefficients according to the relationship

$$\alpha_{12} = (y_1 P_{12}) / (y_2 P_{21}) \quad (6)$$

The ratio  $y_1 P_{12} / y_2 P_{21}$  is nearly constant over a wide range of pressure, so that the relative volatility at any temperature is essentially a function of the ratio of the activity coefficients. Values of the ratio  $y_1 P_{12} / y_2 P_{21}$  are given in Table 12.

Experimental relative volatility results computed according to Equation (5) are plotted in Figures 9a, 9b, and 9c as a function of the water content of the liquid, and with total  $C_4$  hydrocarbon content of the water-free liquid as parameter. Separate plots are given for each relative ratio of isobutane to 1-butene in the liquid. Pre-

vious data (2) for the case of zero water content are included on these plots. Referring to Figure 9 it is seen that the effect of increasing water concentration is to increase the relative volatility of isobutane to 1-butene, although this effect is not so great at higher temperatures. As shown previously for the case of zero water content, the relative volatility is decreased as the  $C_4$  hydrocarbon concentration is increased, or as the temperature is increased.

Prediction of the relative volatility values can most conveniently be made through use of quaternary three-suffix Margules equations which express  $\log \gamma_1 / \gamma_2$  as a function of the liquid composition and the same binary and ternary constants utilized previously:

$$\begin{aligned} \log \frac{\gamma_1}{\gamma_2} = & A_{2-1}(x_2 - x_1) \\ & + x_1(A_{1-2} - A_{2-1})(x_1 - 2x_2) \\ & + x_2(A_{2-2} - A_{1-2}) \\ & + 2x_1(A_{1-2} - A_{1-3}) \\ & - x_1(A_{1-3} - A_{2-3}) \\ & + x_1(A_{1-4} - A_{2-4}) \\ & + 2x_1(A_{2-4} - A_{1-4}) \\ & - x_1(A_{2-4} - A_{2-3}) \\ & - (x_1 C_{123} + x_2 C_{124})(x_2 - x_1) \\ & - x_2 x_1(A_{1-2} - A_{2-3}) \\ & + C_{123} - (A_{2-3} \\ & - A_{2-4} + C_{234}) \end{aligned} \quad (7)$$

Equations for  $\log \gamma_2 / \gamma_1$ ,  $\log \gamma_1 / \gamma_3$ , and  $\log \gamma_1 / \gamma_4$  may be obtained from the above by cyclic permutation of the subscript notation.  $\log \gamma_1 / \gamma_2$  and  $\log \gamma_2 / \gamma_1$  do not follow in this simple way. The equation for  $\log \gamma_3 / \gamma_4$  is given below and  $\log \gamma_4 / \gamma_3$  may be obtained by cyclic permutation:

$$\begin{aligned} \log \frac{\gamma_3}{\gamma_4} = & A_{1-2}(x_3 - x_4) \\ & + x_1(A_{2-1} - A_{1-2})(2x_3 - x_1) \\ & + x_3(A_{3-4} - A_{2-3}) \\ & + x_2(A_{2-3} - A_{1-3}) \\ & - 2x_1(A_{1-3} - A_{1-4}) \\ & + x_1(A_{1-4} - A_{2-4}) \\ & + 2x_1(A_{2-4} - A_{1-4}) \\ & - x_1(A_{2-4} - A_{3-4}) \\ & - (x_1 C_{123} \\ & + x_3(A_{1-2} - A_{2-3}) \\ & + C_{123})(x_3 - x_1) \\ & - x_2 x_1(C_{123}) \\ & - (A_{1-2} \\ & - A_{2-4} + C_{234}) \end{aligned} \quad (8)$$

These relative volatility equations have fewer terms and are simpler to handle than the corresponding equations for the individual activity coefficients. This is because the relative volatility equations are only second-order equations, while the activity coefficient equations are third order equations.

As a first trial in the application of Equation (7) to predict values of relative volatility for comparison with actual values, the ternary constant  $C_{123}$  was taken as zero. This was done in the absence of any specific experimental data for the ternary system isobutane-1-butene-water which are needed to evaluate this constant. All other constants are known from experimental data as described earlier; these values are available from Tables 8 and 9. Figure 13 shows the resulting prediction obtained for the relative volatility of isobutane to 1-butene at 150° F. with a water concentration of 4 wt. % in the  $C_4$  hydrocarbon-free furfural. This plot shows that some improvement in the fit of the equations would be desirable. Use of  $C_{123} = -0.09$ , the consistent value of this constant to be used according to Equation (4) when it is to be assumed that a ternary effect is absent, did not appreciably alter the predicted results.

Improvement of the fit to be obtained with the theoretical equations was at-

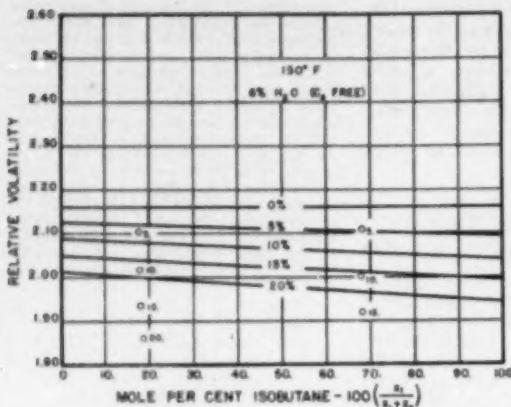


Fig. 11c. Relative volatility of isobutane to 1-butene present in mixtures with furfural and water at 150°F. as a function of the composition  $(100x_1)/(x_1 + x_2)$ . Water concentration in the quaternary liquid is 6 wt. % computed on a  $C_4$  hydrocarbon-free basis. Parameter values are mole per cent total  $C_4$  hydrocarbon in the quaternary liquid computed on a water-free basis. Points are from best lines through experimental data from Fig. 9b. Solid lines are predicted from Eq. (7).

tempted through introduction of larger values for the ternary constant  $C_{130}$ . Referring to Equation (7), it is seen that the terms involving the ternary constants  $C_{130}$  and  $C_{120}$  have no effect upon the relative volatility when  $x_1 = x_2$ . On Figure 13 where the liquid compositions are expressed as  $x_1/(x_1 + x_2)$ , the condition for  $x_1 = x_2$  lies at the mid-point of the abscissa. Thus introduction of larger values for  $C_{130}$  can only serve to pivot the predicted line about the point where  $x_1 = x_2$ . For any assumed value of  $C_{130}$ , the parameter line of  $x_1 + x_2 = 0.5$  will be pivoted most for the case of  $C_{130} = C_{120}$ , while the parameter line  $x_1 + x_2 = 0$  will be unaffected in position regardless of the values of  $C_{130}$  or  $C_{120}$ . Trial-and-error procedure yielded the optimum values of the constant  $C_{130}$  to give a better fit of the experimental data. Figure 11b shows the predicted results obtained for the same conditions as Figure 13 except that the ternary constant  $C_{130}$  had a value of 1.1. The general agreement between predicted and experimental values is considerably improved. Values for the  $C_{130}$  constants obtained in this manner for 100°, 150°, and 200°F. are given in Table 9 and were used in prediction of the quaternary activity coefficient values, as mentioned earlier, as well as for prediction of relative volatility results.

Figures 10a, 10b, 11a, 11b, 11c, 12a, 12b, and 12c show the general agreement obtained between predicted values of relative volatility and those determined experimentally over the wide range of temperature, water concentration, and  $C_4$  hydrocarbon concentration employed in this study. Such agreement gives considerable support for use of the three-suffix Margules equations to extend and correlate multicomponent

vapor-liquid equilibrium data for  $C_4$  hydrocarbon-water-furfural systems.

A cross plot of the results for a water concentration of 4 wt. % on a  $C_4$  hydrocarbon-free basis is shown in Figure 14 as the typical variation of relative volatility with temperature. Temperature variation was quite similar to that found for the  $C_4$  hydrocarbon-dry furfural systems studied earlier (2).

### Simplification of Equations

*Two Components as Single Pseudo-Component.* Simplification of the theoretical treatment of multicomponent equilibrium data may be made by consideration of the liquid mixture of substances 3 and 4 as a homogeneous liquid for the purpose of computing the vapor-liquid equilibrium of substance 1 or of substances 1 and 2. Such a simplification is feasible for the present ternary and quaternary data since the furfural and water components may be considered as a single extractive solvent.

In the following treatment, the three-suffix Margules ternary and quaternary equations are suitably modified so that two of the components are combined into a single pseudocomponent. If, as in the present case, components 3 and 4 are to be treated together, then the mole fraction of the new pseudocom-

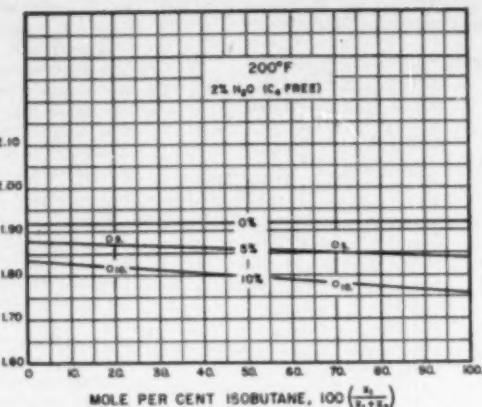


Fig. 12a. Relative volatility of isobutane to 1-butene present in mixtures with furfural and water at 200°F. as a function of the composition  $(100x_1)/(x_1 + x_2)$ . Water concentration in the quaternary liquid is 2 wt. % computed on a  $C_4$  hydrocarbon-free basis. Parameter values are mole per cent total  $C_4$  hydrocarbon in the quaternary liquid computed on a water-free basis. Points are from best lines through experimental data from Fig. 9c. Solid lines are predicted from Eq. (7).

ponent in the liquid may be denoted as  $x_3'$ , and defined as follows:

$$x_3' = x_3 + x_4 \quad (9)$$

Since the equilibrium behavior of any multicomponent mixture is affected by the relative amounts of each component present, only one composition of the pseudocomponent may be considered at any one time. In other words, let

$$x_4/x_3 = K \quad (10)$$

where  $K$  is a constant. As far as the present multicomponent mixtures are concerned, Equation (10) is not a serious limitation since in actual plant operation the water content of the furfural is usually held fairly constant. In other cases where mixed selective solvents are used, the composition is often a certain azeotropic composition, or consists of some component saturated with the second component.

*Pseudo-Binary Equations for Ternary Mixtures.* Substitution of Equations (9) and (10) into the regular three-suffix Margules ternary equations gives:

$$\log \gamma_1 = x_3'^2 [A_{1-3'} + 2x_2(A_{3'-1} - A_{1-3'})] \quad (11)$$

while the corresponding equation for component 2 becomes

$$\log \gamma_2 = x_3'^2 [A_{2-3'} + 2x_1(A_{3'-2} - A_{2-3'})] \quad (12)$$

Equation (11) relates the activity coefficient of component 1 out of a ternary mixture of components 1, 3, and 4 as a function of the liquid composition for the special case of where components 3 and 4 are present in some definite ratio,

TABLE 10  
VALUES OF VAPOR PRESSURE RATIO DIVIDED BY  
GAS LAW CORRECTION RATIO FOR CONVERTING VALUES OF  
ACTIVITY COEFFICIENT RATIO TO RELATIVE VOLATILITY

Temp., °F.	$P_{123}/P_{231}$
100	1.143
150	1.162
200	1.073

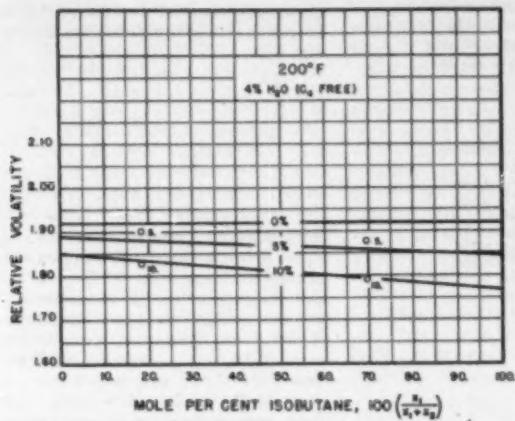


Fig. 12b. Relative volatility of isobutane to 1-butene present in mixtures with furfural and water at 200°F. as a function of the composition  $(100x_1)/(x_1 + x_2)$ . Water concentration in the quaternary liquid is 4 wt. % computed on a C<sub>4</sub> hydrocarbon-free basis. Parameter values are mole per cent total C<sub>4</sub> hydrocarbon in the quaternary liquid computed on a water-free basis. Points are from best lines through experimental data from Fig. 9c. Solid lines are predicted from Eq. (7).

or such that  $x_4/x_3 = K$ . Under these conditions, the constant  $A_{1-2'}$  becomes the logarithm of the value of  $\gamma_1$  as  $x_1$  approaches zero. Similarly, the constant  $A_{3'-1}$  is the logarithm of the activity coefficient for the pseudocomponent as  $x_3'$  approaches zero. For the present case where high C<sub>4</sub> hydrocarbon concentrations were not studied,  $A_{3'-1}$  may be looked upon as merely a second constant required to define the experimental data.

By comparison of the pseudoternary equations with the regular ternary

equations, it may be shown that the constants  $A_{1-2'}$  and  $A_{3'-1}$  are related to the binary and ternary constants of the regular ternary equations as follows:

$$A_{1-2'}(1+K)^2 = A_{1-2} + KA_{3-1} + K(1+K)A_{4-3} - \frac{K}{1+K} [(1-K)A_{4-3} + 2KA_{3-4}] - KC_{134} \quad (13)$$

$$A_{3'-1}(1+K)^2 = (1+K)A_{3-1} + K(1+K)A_{4-3} - \frac{K}{1+K} (A_{4-3} + KA_{3-4}) \quad (14)$$

Similar relationships for  $A_{2-3'}$  and  $A_{3'-2}$  may be obtained by substituting subscript 2 for subscript 1 in the above equations.

The constants  $A_{1-2'}$ ,  $A_{2-3'}$ ,  $A_{3'-1}$ , and  $A_{3'-2}$  were computed from Equations (13) and (14) at values of

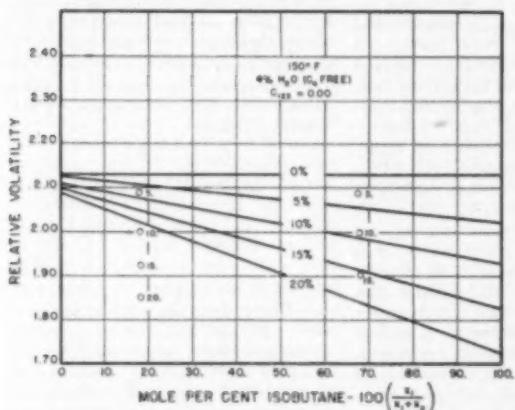


Fig. 13. Relative volatility of isobutane to 1-butene present in mixtures with furfural and water at 150°F. as a function of the composition  $(100x_1)/(x_1 + x_2)$ . Water concentration in the quaternary liquid is 4 wt. % computed on a C<sub>4</sub> hydrocarbon-free basis. Parameter values are mole per cent total C<sub>4</sub> hydrocarbon in the quaternary liquid computed on a water-free basis. Points are from best lines through experimental data from Fig. 9b. Solid lines are predicted from Eq. (7) with the ternary constant  $C_{134} = 0$ .

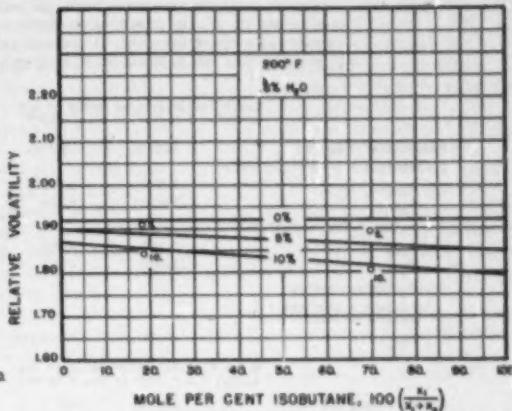


Fig. 12c. Relative volatility of isobutane to 1-butene present in mixtures with furfural and water at 200°F. as a function of the composition  $(100x_1)/(x_1 + x_2)$ . Water concentration in the quaternary liquid is 6 wt. % computed on a C<sub>4</sub> hydrocarbon-free basis. Parameter values are mole per cent total C<sub>4</sub> hydrocarbon in the quaternary liquid computed on a water-free basis. Points are from best lines through experimental data from Fig. 9c. Solid lines are predicted from Eq. (7).

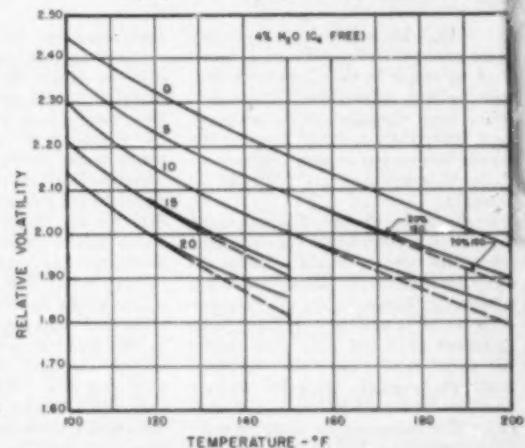


Fig. 14. Typical effect of temperature upon relative volatility of isobutane to 1-butene present in mixtures with furfural and water as a water concentration in the quaternary liquid of 4 wt. % computed on a C<sub>4</sub> hydrocarbon-free basis. Parameter is total mole per cent C<sub>4</sub> hydrocarbon in the quaternary liquid computed on a water-free basis. Solid lines are for a value of  $(100x_1)/(x_1 + x_2) = 20$ , dashed lines are for a value of  $(100x_1)/(x_1 + x_2) = 70$ .

TABLE 13. VALUES OF CONSTANTS FOR PSEUDO-BINARY AND PSEUDO-TERNARY EQUATIONS 11, 12, AND 15 WITH WATER-FURFURAL MIXTURES TREATED AS A SINGLE COMPONENT, AS COMPUTED FROM CONSTANTS OF TABLES VIII AND IX ACCORDING TO EQUATIONS 13 AND 14

Nolar Furfural-Water Ratio in the Liquid = $K = 9.18$ (2 Wt. % Water)			
Pseudo-Binary System	100° F.	150° F.	200° F.
Isobutane - (Water-Furfural)			
$A_{1-3}^1$	1.208	1.120	1.029
$A_{3'-1}$	1.419	1.329	1.067
1-Butene - (Water-Furfural)			
$A_{2-3}^1$	0.910	0.817	0.778
$A_{3'-2}$	1.071	0.972	0.999
Pseudo-Ternary System			
Isobutane - 1-Butene - (Water-Furfural)			
$C_{123}^1$	-0.21	-0.18	-0.16
Nolar Furfural-Water Ratio in the Liquid = $K = 4.50$ (4 Wt. % Water)			
Pseudo-Binary System	100° F.	150° F.	200° F.
Isobutane - (Water-Furfural)			
$A_{1-3}^1$	1.312	1.197	1.104
$A_{3'-1}$	1.515	1.290	1.100
1-Butene - (Water-Furfural)			
$A_{2-3}^1$	0.978	0.912	0.853
$A_{3'-2}$	1.120	0.992	0.902
Pseudo-Ternary System			
Isobutane - 1-Butene - (Water-Furfural)			
$C_{123}^1$	-0.20	-0.17	-0.14
Nolar Furfural-Water Ratio in the Liquid = $K = 2.94$ (6 Wt. % Water)			
Pseudo-Binary System	100° F.	150° F.	200° F.
Isobutane - (Water-Furfural)			
$A_{1-3}^1$	1.409	1.282	1.184
$A_{3'-1}$	1.612	1.350	1.133
1-Butene - (Water-Furfural)			
$A_{2-3}^1$	1.090	0.989	0.934
$A_{3'-2}$	1.161	1.020	0.910
Pseudo-Ternary System			
Isobutane - 1-Butene - (Water-Furfural)			
$C_{123}^1$	-0.19	-0.16	-0.12

$K = 9.18$ ,  $4.50$ , and  $2.94$  corresponding to the previous designations of  $2$ ,  $4$ , and  $6$  wt. % water in the  $C_4$  hydrocarbon-free furfural, respectively. These constants were computed at the temperatures  $100^\circ$ ,  $150^\circ$ , and  $200^\circ$  F. using the regular binary and ternary constants of Tables 8 and 9 and are presented in Table 13.

It should be obvious that values of the activity coefficients for isobutane out of the ternary mixture isobutane-water-furfural or the activity coefficient values for 1-butene out of 1-butene-water-furfural mixtures predicted from Equations (11) and (12) give exactly the same results as those predicted from the regular Margules ternary equations presented earlier as Equation (2). The advantage of using pseudobinary equations for ternary mixtures lies in their greater simplicity in expressing ternary results with only two constants. Also, if ternary data are known without full knowledge of the corresponding binary systems, use of pseudobinary equations to express the ternary results is especially helpful since the constants such as  $A_{1-3}$ , of

these equations can be determined directly from the ternary experimental data in much the same manner as Margules binary constants are obtained from binary data. For the present case, the ternary data for the systems isobutane-water-furfural and 1-butene-water-furfural were determined accurately and are probably more precise than data for the binary systems isobutane-water and 1-butene-water for which solubilities are extremely low, so that evaluation of the pseudobinary constants might have been made directly from the experimental ternary data rather than from the corresponding binary constants through Equations (13) and (14). However, representation of the ternary data through use of the regular three-suffix Margules equations was excellent as shown in an earlier section, so that either method of determining the pseudobinary constants appears satisfactory.

*Pseudo-Ternary Equations for Quaternary Mixtures.* Substitution of the relationships  $x_3 + x_4 = x_3'$ , and  $x_4/x_3 = K$  in the three-suffix Margules

quaternary equation for the prediction of relative volatility yields the following:

$$\log \frac{y_1}{y_2} = A_{2-1}(x_2 - x_1) + x_2(A_{1-2} - A_{2-1})(x_2 - 2x_1) + x_3(A_{1-3} - A_{3-2}) + 2x_1(A_{3'-1} - A_{1-3}) - x_3(A_{3-3} - A_{3'-2}) - C_{123}(x_2 - x_1) \quad (15)$$

This equation presents values of  $\log y_1/y_2$  out of a quaternary mixture consisting of components  $1$ ,  $2$ ,  $3$ , and  $4$  as a function of the liquid composition for the special case where components  $3$  and  $4$  are present in some definite ratio,  $x_4/x_3 = K$ . Inspection of Equation (15) shows that it is similar in form to the regular three-suffix Margules ternary equation for the relative volatility with the exception that the subscript  $3$  in the regular ternary equation has been replaced with the subscript  $3'$  in Equation (15) above. This relationship is general, and pseudoternary equations for activity coefficients in a quaternary system may be written from the regular ternary equation for activity coefficients (Equation (2)) by the same procedure. The constants  $A_{1-3}$ ,  $A_{3'-1}$ ,  $A_{3-3}$ , and  $A_{3'-2}$  have the same significance as defined earlier. They may be obtained from ternary data through the pseudobinary Equations (11) and (12) (or those corresponding to Equations (11) and (12) in which subscript  $1$  is replaced by  $2$ ), or they may be obtained through the regular ternary equations used together with Equations (13) and (14) and their analogues. In cases where the ternary constants  $C_{134}$  and  $C_{234}$  are small and may be neglected, the constants  $A_{1-3}$ , etc., may be obtained from binary data using Equations (13) and (14). The constant  $C_{123}$  is not a quaternary constant but is made up from the following combination of binary and ternary constants as follows:

$$C_{123}(1+K)^2 = (C_{123} + KC_{134})(1+K) - K(A_{1-3} - A_{3-1} + C_{134}) - \frac{K^2}{1+K} (A_{3-4} - A_{4-3}) \quad (16)$$

Values of the constant  $C_{123}$  were computed from Equation (16) at values of  $K = 9.18$ ,  $4.50$ , and  $2.94$  corresponding to the previous designations of  $2$ ,  $4$ , and  $6$  wt. % water in the  $C_4$  hydrocarbon-free furfural, respectively. These constants were computed at the temperatures  $100^\circ$ ,  $150^\circ$ , and  $200^\circ$  F. using the regular binary and ternary constants of Tables 8 and 9 and are presented in Table 13. Results predicted by Equations (15) and (16) are of course identical with those presented earlier based upon the regular quaternary equations since the pseudoternary equations are

an exact but specific form of the quaternary equations. Use of Equation (15) for the quaternary system of this study is considerably simplified since the binary constants  $A_{1-2}$  and  $A_{2-3}$  are both zero.

Inspection of the values of  $C_{123}$  in Table 13 shows them to be nearly independent of water concentration and practically identical in magnitude with the ternary constant  $C_{123}$  for the system isobutane-1-butene-furfural. Also, both the constants vary with temperature in the same manner. These facts would imply that for the present system the presence of water in the quaternary system causes no additional change in behavior above its effect upon each of the ternary systems. Such a conclusion is not unexpected, but is extremely important. If it had been known beforehand, the quaternary data could have been predicted in a simple manner through Equation (15) from the results of only the two ternary systems determined earlier. Extension of ternary data to predict quaternary results for other  $C_4$  hydrocarbon-water-furfural systems is greatly simplified if the same conclusion may also be applied.

The form of the pseudoternary relative volatility equation (Equation (15)) allows for a simple determination of the constant  $C_{123}$  directly from the quaternary data. It should be noted that for the case of  $x_1 = x_2$ , the term involving  $C_{123}$  vanishes, so that when results are plotted as  $\alpha$  vs.  $x_1/(x_1 + x_2)$ , as in Figures 9-13, a change in the value of  $C_{123}$  can only pivot each  $x_1 + x_2$  parameter line around the point where  $x_1/(x_1 + x_2) = 0.50$ . Thus once good agreement between predicted and experimental points is obtained in the region where the constant  $C_{123}$  has no effect, values of  $C_{123}$  may be computed from experimental data points in the concentration region affecting  $C_{123}$  the most. The values of  $C_{123}$  given in Table 13 were not computed by this procedure, however, but were obtained from Equation (16) utilizing the regular binary and ternary constants. This was done in view of the good agreement with the experimental data previously obtained using the regular binary and ternary constants in the regular quaternary equations.

It should be remembered that in an earlier section the ternary constant  $C_{123}$  for the ternary system isobutane-1-butene-water was not known experimentally and was chosen by trial according to the best fit obtained between the quaternary equations and the quaternary data. Evidence that the chosen values of  $C_{123}$  are correct is shown by the good agreement obtained between both the regular quaternary equations and the pseudoternary equations with the experimental data. Also, the fact that the values of  $C_{123}$  are reasonable as dis-

cussed here supports the reliability of  $C_{123}$  since values of  $C_{123}$  were computed from  $C_{123}$  and other proved constants in Equation (16).

Use of pseudoternary equations for correlation and prediction of quaternary results is greatly to be recommended, even for cases unlike the present one where all components have appreciable volatility. When for example four components are present and it is desired to express results graphically in terms of  $\log y_1$  as a function of  $x_1$ , it is still necessary to specify two composition ratios as parameters. Under these conditions the pseudoternary equations with the requirement that only one composition ratio be constant offer a logical choice as the most workable and simple equations for use.

### Conclusion

Addition of water to isobutane and 1-butene in mixtures separately or together with furfural causes appreciable increase in the activity coefficient values for each  $C_4$  hydrocarbon out of the liquid mixture. Although the volatility of each  $C_4$  hydrocarbon component is increased, the relative volatility of the isobutane to 1-butene is only slightly increased as the water concentration is increased.

Correlation of results through use of three-suffix Margules equations was entirely satisfactory in the range of composition and temperature investigated. Since the activity coefficient results varied over a wide range, whereas the relative volatility results were nearly constant by comparison, the same percentage deviation between experimental and predicted results appears much larger on the expanded scale of the relative volatility plots.

### Acknowledgment

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### Notation

$A_{1-2}$  = limit  $\log y_1(x_1 \rightarrow 0, x_2 \rightarrow 1)$

$A_{2-3}$ , etc. = limit  $\log y_2(x_2 \rightarrow 0, x_3 \rightarrow 1)$

$B_1$  = second virial coefficient of component 1 in the equation of state

$C_{123}$  = ternary constant of three-suffix Margules equation for ternary system of components 1, 2, and 3

$C_{234}$ , etc. = ternary constant of three-suffix Margules equation for ternary system of components 2, 3, and 4

$P$  = total pressure

$P_1, P_2$   
 $P_3, P_4$  = vapor pressures of pure components

$R$  = gas law constant

$T$  = absolute temperature

$v_1$  = liquid specific volume for component 1

$x$  = mole fraction of component in the liquid

$y$  = mole fraction of component in the vapor

$z$  = correction for nonideality of gases and volume of liquid, or  $a_1 = \text{Exp}_{10}(P_1 - P)(v_1 - B_1)/2.303 RT$

$a_{12}$  = relative volatility of component 1 to component 2 or  $(y_1/x_1)/(y_2/x_2)$

$\gamma$  = activity coefficient of component

### SUBSCRIPTS:

1 = component 1, isobutane

2 = component 2, 1-butene

3 = component 3, water

4 = component 4, furfural

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(Presented at Thirteenth Regional Meeting, Houston, Tex.)

### CORRECTION

In "Heat and Mass Transfer in Fluidized Systems," by K. N. Kettnering, E. L. Manderfield, and J. M. Smith (March, 1950, page 139), the second equation of the abstract should read 0.0180 instead of 0.00180. This same error occurred in Equation (10) on page 144 of the article.

# CATALYTIC OXIDATION OF SULFUR DIOXIDE

## EFFECT OF DIFFUSION

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The importance of diffusion in the catalytic oxidation of sulfur dioxide was determined experimentally by measuring the rate of oxidation in a flow reactor operated at various mass velocities. The catalyst consisted of platinum, coated on  $\frac{1}{8}$  in. cylindrical pellets. The reactor I.D. was 1.5 in. and the catalyst bed depth low in order to approach differential reaction conditions. The mass velocity was varied from 147 to 514 lb./hr.(sq.ft.) and the temperature from 350 to 480° C.

It was found that the use of available data for the diffusion rates to the catalyst surface gave a satisfactory method of accounting for the effect of diffusion. It was found further that at high temperatures, low mass velocities, and low conversions, the pressure drop between the main gas and the catalyst surface for sulfur dioxide was as much as 25% of the partial pressure of sulfur dioxide in the gas. At low temperatures and high mass velocities the pressure drop was negligible.

THE design of equipment for gaseous reactions in which a solid catalyst is used may require consideration of the physical process of diffusion as well as the adsorption, reaction, and desorption steps at the catalyst surface. Diffusion of reactants and products between the gas in the stream and the catalyst is likely to be important at high temperatures, where the surface rate of reaction is high, and at low gas mass velocities, where the mass-transfer coefficients are low. The mass-transfer coefficients are primarily dependent upon the gas mass velocity and nearly independent of temperature. On the other hand, the adsorption, reaction, and desorption steps

are independent of mass velocity and vary with temperature. Because of this situation the relative importance of the mass transfer and surface processes in establishing the over-all rate of reaction can be evaluated by operating a reactor under varying conditions of mass velocity and temperature.

The purpose of this investigation was to determine the importance of diffusion by measuring reaction rates at different temperatures and mass velocities for the oxidation of sulfur dioxide with a platinum catalyst. In analyzing the experimental results, the main objective was to compare the theoretical methods for taking into account the effect of

diffusion on the rate with the observed data. Apparently the only other experimental information on this subject is that of Hurt (7) who has introduced the concepts of the H.R.U. (height of reaction unit) and pseudo-first-order reaction mechanism and applied them to the oxidation of sulfur dioxide.

Reaction rates were also measured as a function of one composition variable, the extent of conversion of the sulfur dioxide. These data were used then to test the proposals of Uyehara and Watson (9) and Hurt (7) for the mechanism controlling the rate of reaction at the catalyst surface. However, since the partial pressures of reactants and products were not varied independently and since diffusion effects always had to be accounted for, the study of reaction mechanisms was only a secondary objective of this investigation.

### Scope of Work

Reaction rates were measured in a 1.5-in. I.D., differential reactor packed with  $\frac{3}{4}$  in.  $\times \frac{1}{8}$  in. cylindrical, alumina pellets coated with platinum. The range of operating conditions was as follows:

Temperature: 350-480° C.

Pressure: 790 mm. Hg.

Gas mass velocity: 147-514 lb./hr.(sq.ft. of empty reactor area)

Conversion: 4-70%

**Apparatus and Procedure.** The apparatus and procedure used in this investigation were similar to those discussed by Hall and Smith (3) and are as follows:

1. Pretreatment and metering of reactants
2. Preconversion of part of the sulfur dioxide in the preconverter
3. Measurement of the reaction rate in the differential reactor
4. Analysis of reactant and product gases

A schematic diagram of the apparatus is shown in Figure 1. Air was passed through a fiber-glass filter to remove entrained oil and then dried in two silica gel driers operated in series. The dried air was metered with a precision rotameter, 30 in. length. The air was preheated approximately to reaction temperature in an electric heater and then passed through a preliminary con-

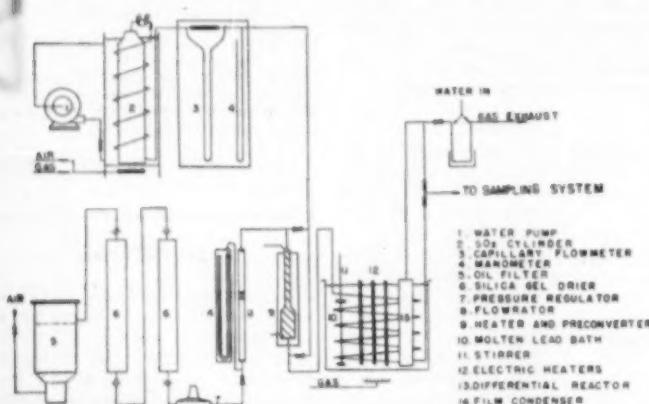


Fig. 1. Schematic diagram of apparatus.

verter. Sulfur dioxide was metered with a glass capillary flowmeter and also passed to the preconverter. The conversion to sulfur trioxide obtained in the preconverter permitted the investigation of rates in the presence of sulfur trioxide. Arrangements were available for admitting sulfur dioxide either before or after the preconverter, the amount admitted before being governed by the percentage of preconversion desired. The preconverter consisted of a stainless steel tube, 4 in. in length and 1.5 in. in diameter, fitted with retaining screens to hold the catalyst in place. A chromel-alumel thermocouple placed in the catalyst bed permitted maintaining a constant temperature sufficiently high to ensure approximately complete conversion.

The reactants passed through a 1-in. stainless steel coil packed with  $\frac{1}{2}$ -in. Rasching rings and immersed in a constant-temperature, lead bath. The stainless steel differential reactor was 15-in. I.D. and packed with catalyst to a depth of only  $\frac{1}{4}$  in. in order to limit the conversion to low values and so obtain approximately differential rates. Details of the reactor are shown in Figure 2. Three chromel-alumel thermocouples, with leads contained in  $\frac{1}{8}$ -in. stainless-steel tubes open at both ends, were used to measure the center and edge catalyst temperatures and the exit gas temperature. Thermocouple junctions used to measure catalyst temperatures were imbedded in the  $\frac{1}{2}$ -in. pellets.

After leaving the differential reactor, the product gases passed through a stainless steel valve, used to control the system pressure at an average value of 790 mm., and finally through a cooler.

Samples of the reactant and product gases were withdrawn through stainless steel pipes on either side of the differential reactor and analyzed by the volumetric oxidation method described by Hall and Smith (7).

The catalyst consisted of 0.2 wt. % platinum coated on  $\frac{1}{8}$  by  $\frac{1}{8}$  in. cylindrical alumina pellets. The catalyst bed normally used contained 10.5 g. and was three pellets deep. Some runs were made with a mixture of 5.0 g. of catalyst and 5.5 g. of plain alumina pellets.

It was found that the activity of the catalyst decreased during the first day's operations (approximately 7 hr.) and reached a constant activity on the following day. It was found further that the reduction in activity was determined by the time measured from the initial contact with sulfur dioxide rather than the total on-stream time. A plot of reaction rate vs. on-stream is shown in Figure 3. Moisture had a pronounced poisoning effect on the catalyst, and, as a result, careful regeneration of the drying agent was required. To minimize the moisture problems, refrigeration or research grade sulfur dioxide was used in all the runs.

*Experimental Results.* Differential reaction rate data at the four mass velocities (based upon the cross-sectional area of the empty reactor) are shown in Tables 1-4. These data were obtained using but one initial concentration of reactants entering the preconverter (6.42 mole %  $\text{SO}_2$  and the remainder air). However, the effect of restricted composition changes on the rate were determined by runs made at 0-70% preconversion obtained in the preconverter

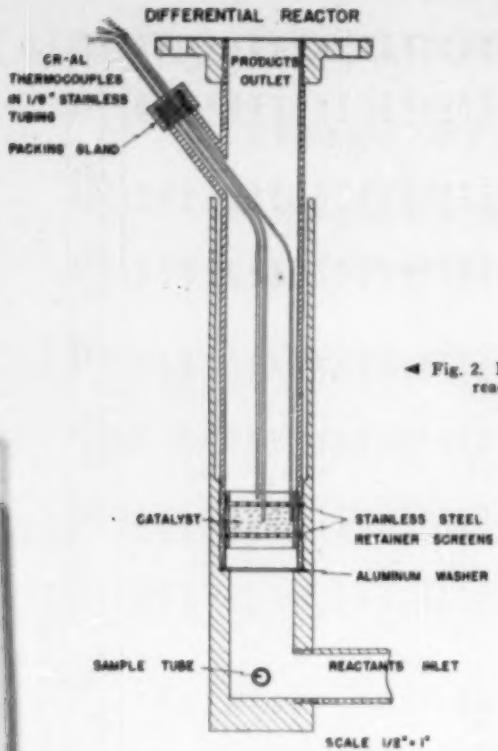


Fig. 2. Differential reactor.

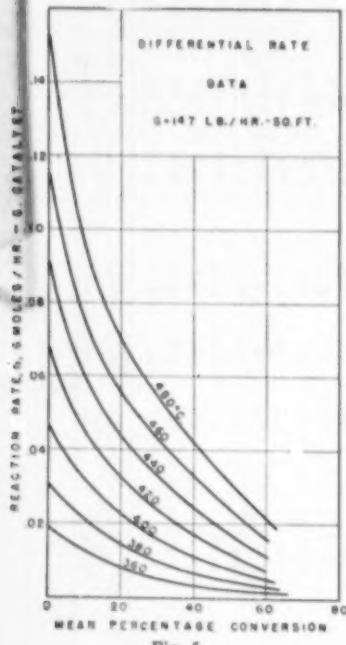


Fig. 3.

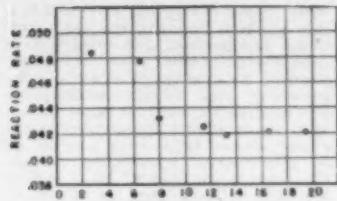


Fig. 3. Reaction rate as function of "on stream" time, hrs.  
 "on stream" time.  
 Temperature 411°C.  
 Mass velocity—245 lb./hr.  
 (sq. ft.)

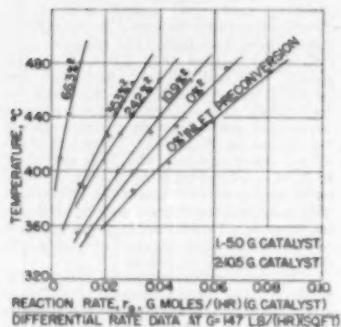


Fig. 4

upstream from the differential reactor. Thus the composition changes can be expressed in terms of one variable, the extent of conversion.

Because of the highly exothermic reaction, it was impossible to maintain the catalyst bed at an exactly uniform temperature. The thermocouples at the edge and center indicated temperature differences of several degrees, especially at high temperatures and low preconversions. In order to represent the data accurately as a function of temperature, the following method was employed to calculate the best average temperature of the bed: a parabola was chosen to represent the radial temperature curve and then fitted to the known temperatures at the center and edge of the bed. The area-average temperature was evaluated by integration. The parabola was chosen because it was found (3) to fit experimental curves rather well.

The errors in the rate measurements varied with the temperature and conversion. At a low temperature, the small conversions tended to decrease the accuracy of the analytical method but increase the accuracy of the average temperature calculation. At low mass velocities, the low space velocities resulted in relatively high conversions and radial temperature gradients, which increased the deviation from differential conditions in the catalyst bed. The lower weight of active catalyst (5.0 g.) was used under these conditions in order to minimize this problem.

Using the original data in Tables 1-4, plots were made of the reaction rate versus temperature with parameters of constant

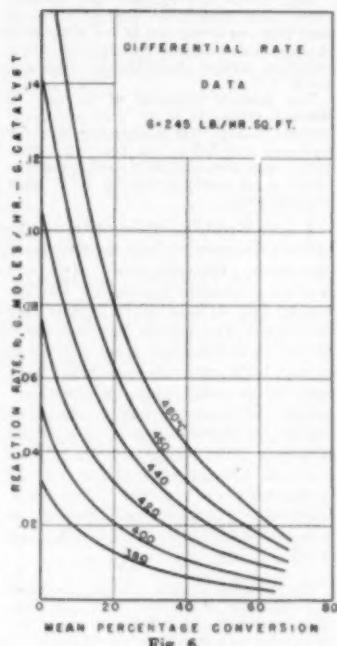


Fig. 6

incoming conversion; that is, constant conversion entering the differential reactor. A typical plot is shown in Figure 4 for a mass velocity of 147 lb./(hr.) (sq.ft.). Values from these curves were then cross- plotted as reaction rate versus mean per-

cent conversion, with lines of constant temperature. Results are shown in Figures 5-8. Use of mean conversion (the average of inlet and exit conversions from the differential reactor) gives a closer approach to truly differential reaction rates than the original incoming preconversion. Arithmetic averaging was used to evaluate

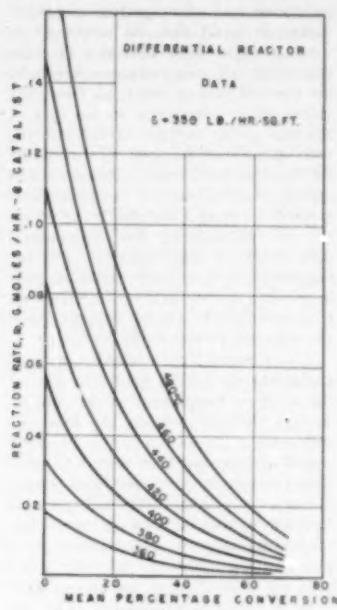


Fig. 7.

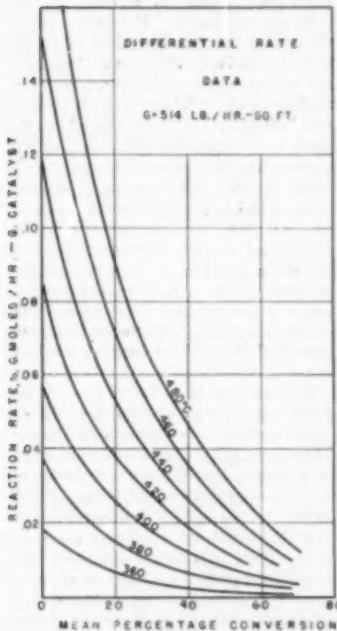


Fig. 8

the mean conversion, since the exit values were always less than twice the inlet conversions (except for those runs made with 0% SO<sub>2</sub> entering the differential reactor).

Data in Figures 5-8 show that the presence of small amounts of sulfur trioxide produces a pronounced retardation of the reaction. This is in qualitative agreement with the earlier results of Bodenstein and Fink (2) and Lewis and Ries (8).

Figure 9 is a cross-plot of the data in Figures 5-8 showing the effect of mass

velocity on the rate at a constant conversion of 10%. As expected, the curves tend to approach a constant rate as the mass velocity increases, indicating the decreasing effect of diffusion resistances at high velocities. This figure also shows that the relative importance of mass velocity becomes less as the temperature goes down.

*Methods of Evaluating Effect of Diffusion.* There are several methods by which rate data at different mass veloci-

TABLE 3.—DIFFERENTIAL REACTION RATE DATA  
MASS VELOCITY = 200 lb./in.<sup>2</sup>·hr. (eq. %)

Run No.	Temperature, °C.	Catalyst Gel Catalyst Percentage Remaining After Pyrolysis	Catalyst Gel Catalyst Percentage Remaining After Pyrolysis	Mean Velocity (lb./in. <sup>2</sup> ·hr.)		Mean Velocity (lb./in. <sup>2</sup> ·hr.)					
				100	150						
4-7	346.4	149.8	349.0	148.2	149.7	0.0077	0.0072	0.0075	0.0074	0.0075	0.0074
4-8	375.3	188.6	386.9	153.5	0.0076	0.0073	0.0072	0.0071	0.0070	0.0070	0.0070
4-9	403.4	427.2	429.5	429.5	0.0077	0.0072	0.0072	0.0071	0.0070	0.0070	0.0070
4-10	425.1	457.2	453.5	453.5	0.0077	0.0073	0.0073	0.0072	0.0071	0.0071	0.0071
4-11	353.9	353.3	353.6	353.0	0.0076	0.0071	0.0071	0.0071	0.0070	0.0070	0.0070
4-12	389.5	397.0	396.3	396.9	0.0075	0.0072	0.0072	0.0071	0.0070	0.0070	0.0070
4-13	421.7	438.9	436.7	436.0	0.0077	0.0072	0.0072	0.0071	0.0070	0.0070	0.0070
4-14	388.7	392.3	392.5	392.7	0.0076	0.0072	0.0072	0.0071	0.0070	0.0070	0.0070
4-15	423.2	429.4	428.7	428.6	0.0076	0.0072	0.0072	0.0071	0.0070	0.0070	0.0070
4-16	405.5	403.3	403.5	403.5	0.0077	0.0072	0.0072	0.0071	0.0070	0.0070	0.0070
4-17	390.5	392.0	392.8	392.3	0.0076	0.0072	0.0072	0.0071	0.0070	0.0070	0.0070
4-18	429.9	445.2	444.2	445.3	0.0076	0.0072	0.0072	0.0071	0.0070	0.0070	0.0070
4-19	419.0	408.8	408.2	408.2	0.0079	0.0076	0.0076	0.0075	0.0074	0.0074	0.0074
4-20	408.7	403.9	403.8	403.8	0.0079	0.0076	0.0076	0.0075	0.0074	0.0074	0.0074
4-21	390.3	393.3	393.5	393.5	0.0079	0.0076	0.0076	0.0075	0.0074	0.0074	0.0074
4-22	386.3	387.3	387.3	387.3	0.0079	0.0076	0.0076	0.0075	0.0074	0.0074	0.0074
4-23	406.4	420.0	419.0	419.0	0.0080	0.0076	0.0076	0.0075	0.0074	0.0074	0.0074
4-24	423.7	438.4	438.4	438.4	0.0079	0.0076	0.0076	0.0075	0.0074	0.0074	0.0074
4-25	444.6	473.0	473.0	473.4	0.0079	0.0076	0.0076	0.0075	0.0074	0.0074	0.0074

Average Mass Velocity = 200

ties can be analyzed to evaluate quantitatively the importance of diffusion. One approach would be to extrapolate  $r$  vs.  $G$  curves, such as those shown in Figure 9, in order to evaluate the rate  $r_{\infty}$  at infinite mass velocity. This rate would correspond to the case of no diffusion resistance and represents a maximum value. It could then be compared to rates at finite mass velocities to show how much diffusion resistance decreases the over-all rate of reaction. Since the values of  $r_{\infty}$  correspond to the rate of reaction at the surface of the catalyst, such data could be used to investigate the reaction mechanism. However, this method may be subject to considerable error in its application due to the necessity of extrapolating the experimental data to infinite mass velocity. The extrapolation can be made more accurate by plotting  $1/r$  vs.  $1/G$  rather than  $r$  vs.  $G$  as in Figure 9. On the reciprocal plot the intercept gives a value for  $1/r_{\infty}$ .

An approach that is similar involves evaluating the partial pressures ( $p_i$ ) of the reaction components at the catalyst surface by extrapolating  $p_g$  data. In this scheme graphs similar to Figure 9 would be prepared with curves for different values of  $p_g$ . From these graphs corresponding values of  $G$  and  $p_g$  could be read at a fixed rate of reaction  $r$ . Extrapolation of this information on a plot of  $p_g$  vs.  $1/G$  (to  $1/G = 0$ ) would give the desired  $p_i$  at the chosen rate.

Both previous procedures have the advantage of not necessitating auxiliary experimental data in addition to the rate measurements. However, unless the rate of reaction is studied at a number of relatively high mass velocities, the extrapolation requirement may introduce errors. When data at only a few values of  $G$  are available, the method of evaluating diffusional effects proposed by Hougen and Watson (5) is more useful. This approach depends upon utilizing available correlations of mass-transfer coefficients to calculate the partial-pressure differences between the main gas stream and the catalyst surface. Once the partial-pressure values at the surface are evaluated they can be used along with the experimental rate data to study the reaction mechanism.

The method used by Hurt (7) depends upon the assumption that the reaction mechanism is pseudo first order. Then separation of the resistances due to diffusion and the surface processes can be accomplished by using the H.T.U. to represent the former and the H.C.U. (height of a catalyst unit) the latter. This approach is similar to that proposed by Hougen and Watson in that it also depends upon the use of additional data to evaluate the diffusional resistances, that is, correlations of

1.  $\frac{1}{2}$  Extrapolation from runs 4-13.

2.  $\frac{1}{2}$  Extrapolation is average of runs 17 and 19.

3.  $\frac{1}{2}$  Extrapolation is average of runs 17 and 19.

mass-transfer coefficients or H.T.U. values. The scheme proposed by Hurt is easier to apply but cannot be used to investigate the nature of the reaction mechanism at the catalyst surface.

Rate data obtained in this study have been analyzed by Hougen and Watson's and Hurt's methods. The extrapolation procedure has not been used because only four mass velocities were studied, and the maximum was only 514 lb./hr. (sq.ft.).

**Film Pressure Drop** ( $p_g - p_i$ ) Due to Diffusion. In evaluating the partial pressure of reactants ( $\text{SO}_2$  and  $\text{O}_2$ ) and product ( $\text{SO}_3$ ) at the catalyst surface, the mass-transfer correlations of Hougen and Wilkie (6) were employed. At modified Reynolds numbers below 350, their results can be written in terms of a mass-transfer coefficient  $k_g$  for  $\text{SO}_2$  as follows:

$$(k_g)_{\text{SO}_2} = \frac{1.82 G \left( \frac{d_g G}{\mu} \right)^{0.51}}{M_m \rho_f} \left( \frac{\mu}{\rho D_{\text{SO}_2}} \right)^{0.51} \quad (1)$$

where  $D_{\text{SO}_2}$  represents the mean diffusivity of  $\text{SO}_2$  in the diffusing mixture of  $\text{SO}_2$ ,  $\text{O}_2$ ,  $\text{SO}_3$  and  $\text{N}_2$ .

The rate of mass transfer across the film is equal to the rate of reaction and may be expressed by the equation,

$$r = (k_g)_{\text{SO}_2} a (\rho_g - \rho_i) \quad (2)$$

If  $r$  is the rate per unit mass of catalyst, then  $a$  becomes the catalyst particle area per unit mass. For the  $\frac{1}{8}$  in.  $\times \frac{1}{8}$  in. cylindrical pellets used in this work the pellet density was 112.8 lb./cu.ft. and  $a = 5.12 \text{ sq.ft./lb.}$

Combination of Equations (1) and (2) gives the required expression for the pressure drop across the film.

$$(\rho_g - \rho_i)_{\text{SO}_2} = \frac{r M_m \rho_f}{9.32 G} \left( \frac{d_g G}{\mu} \right)^{0.51} \left( \frac{\mu}{\rho D_{\text{SO}_2}} \right)^{0.51} \quad (3)$$

This equation was employed to evaluate  $\rho_i$  values for  $\text{SO}_2$  from the experimental rate and mass velocity. The pressure film factor  $\rho_f$  (analogous to the mean partial pressure of inert gas in the case of a single diffusing component in a stagnant gas) was evaluated according to the procedure proposed by Wilkie (10). Because of the large partial pressure of nitrogen in the reaction mixture, the  $\rho_f$  values did not change significantly across the film. This eliminated the necessity for trial and error procedures and simplified the calculations considerably.

The diffusivity of sulfur dioxide in the diffusing reaction mixture was also evaluated according to the procedure outlined by Wilkie (10). Calculations

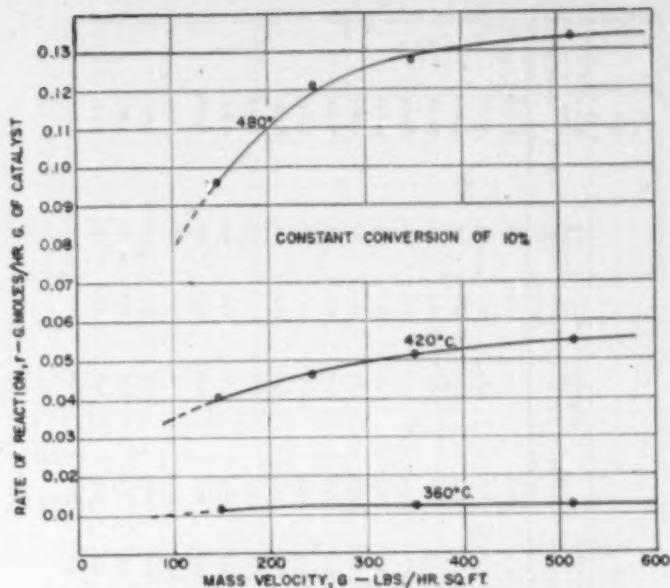


Fig. 9. Effect of mass velocity upon rate of reaction.

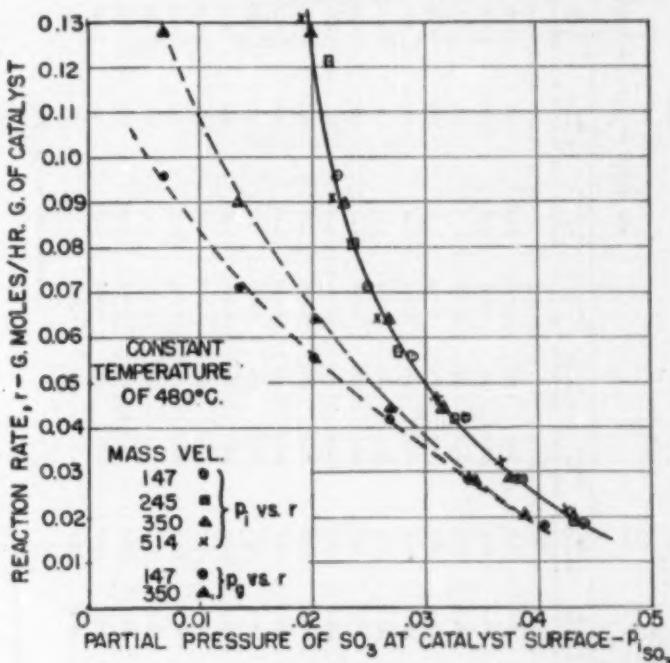


Fig. 10.

were simplified because the small composition changes of the whole gas mixture with conversion did not affect the Schmidt group.

Equations similar to (3) were used

to determine  $(\rho_g - \rho_i)$  for  $\text{O}_2$  and for  $\text{SO}_3$ . Results are summarized in Table 5, which shows  $\rho_g - \rho_i$  and  $\rho_i$  for various mass velocities, temperatures, and conversion.

TABLE 4  
EXPERIMENTAL REACTION RATE DATA  
MASS VELOCITY (lb. SO<sub>2</sub>/hr.-sq.ft.-feet.)

Run No.	Run No.	Glycerol Temperature, °C.	Sulfur Oxide Temperature, °C.	Glycerol Gasoline Temperature, °C.	Peroxide Concentration Temperature, °C.	Open holes SO <sub>2</sub> /hr.	Rate of air/hr.	Rate of air/hr.	S. Conversion		S. Conversion at 100% conversion	Weight loss at 100% conversion (grams)
									Rate of air/hr.	Rate of air/hr.		
2-15	340-9	254-8	352-3	353-2	364-	0.0960	3-65	335-	6-39	0-0	2-34	10-5
2-16	370-0	302-4	397-9	396-0	380-	0.0960	3-65	300-	6-39	0-0	6-75	10-5
2-17	426-0	432-3	424-3	424-3	422-	0.0960	3-65	521-	6-32	0-0	12-1	10-5
2-18	439-1	460-1	448-0	471-5	471-	0.0960	3-65	521-	6-32	0-0	21-2	10-5
2-19	369-8	371-3	370-8	370-8	368-	0.0960	3-65	521-	6-35	20-9	22-6	0-46
2-20	412-0	412-7	408-2	408-2	408-	0.0960	3-65	527-	6-34	20-3	22-5	0-28
2-21	432-8	430-4	421-3	421-3	421-	0.0960	3-62	513-	6-45	20-3	4-53	10-5
2-22	432-1	442-5	444-6	444-6	442-	0.0960	3-62	512-	6-44	20-3	8-30	10-5
2-23	459-0	480-9	472-5	475-5	477-	0.0960	3-62	513-	6-46	21-5	11-80	10-5
2-24	398-1	399-8	390-0	390-0	391-	0.0960	3-62	513-	6-43	27-6	2-80	10-5
2-25	420-1	427-0	423-7	424-0	420-	0.0977	3-43	513-	6-40	27-3	43-3	10-5
2-26	425-1	425-0	405-0	405-0	406-	0.0976	3-40	511-	6-49	54-5	51-4	10-5
2-27	423-4	469-5	465-7	468-2	467-	0.0976	3-40	511-	6-49	54-5	3-50	10-5
2-28	397-6	430-3	390-8	390-8	390-	0.0960	3-43	514-	6-43	33-8	2-43	10-5
2-29	423-8	423-8	423-7	424-0	424-	0.0960	4-34	514-	6-42	34-8	4-06	10-5
2-30	393-8	423-7	400-0	400-0	400-	0.0960	3-42	510-	6-47	0-0	5-46	5-2
2-31	424-1	424-1	424-1	424-1	424-	0.0960	3-42	511-	6-47	0-0	4-41	5-2
2-32	457-1	457-1	457-1	457-1	457-	0.0960	3-42	510-	6-47	0-0	12-93	5-2
2-33	453-7	480-0	472-1	472-	472-	0.0960	3-42	510-	6-47	0-0	22-9	5-2

Average Mass Velocity = 524.

Conversion from percent to.

The reliability of this scheme of taking into account the effect of diffusion is illustrated in Figure 10, where the reaction rate is plotted vs. the values of  $p_t$  for SO<sub>3</sub> calculated by the Equation for SO<sub>3</sub> analogous to (3). It is apparent that the results for the four different mass velocities fall approximately on a single curve, showing that Equation (3) satisfactorily eliminates the effect of diffusion. For comparison, values of  $p_g$  are also shown on the figure (as solid points) for the two mass velocities of 147 and 350 lb./hr. (sq.ft.). The deviation between these two  $p_g$  vs.  $r$  curves is considerable, illustrating the need for correcting for diffusion. A similar plot showing  $p_t$  for SO<sub>2</sub> is presented in Figure 11. As expected from the results of Figure 10, the points for different mass velocities again fall close to a single curve.

The criterion that the data for all mass velocities must fall on a single curve in Figure 10 and 11, if diffusion is to be accounted for satisfactorily, may not be immediately apparent. It is based upon the existence of a relationship between  $p_t$  values for SO<sub>2</sub>, SO<sub>3</sub>, and O<sub>2</sub> which is nearly independent of mass velocity. Such a relationship did exist in this investigation because of two things: (1) the composition of the reaction mixture was varied only by conversion, and (2) the particular values of the diffusivities of SO<sub>2</sub>, SO<sub>3</sub>, and O<sub>2</sub>. For example, if Equation (3) is applied to SO<sub>2</sub> and SO<sub>3</sub> and the  $p_g$  quantities eliminated by the stoichiometry of the reaction, the following equation results:

$$p_{tSO_3} = \frac{X_{SO_3} p_t - p_{SO_2}}{1 - 0.5X_{SO_3}} + \left( K_{SO_3} - \frac{K_{SO_2}}{1 - 0.5X_{SO_3}} \right) r G^{-0.49} \quad (4)$$

where

$$K_{SO_3} = \frac{M_m p_t}{1.82a} \left( \frac{d_p}{\mu} \right)^{0.51} \left( \frac{\mu}{\rho D_{SO_3}} \right)^{1/2} \quad (5)$$

$$K_{SO_2} = \frac{M_m p_t}{1.82a} \left( \frac{d_p}{\mu} \right)^{0.51} \left( \frac{\mu}{\rho D_{SO_2}} \right)^{1/2} \quad (6)$$

The value of  $X_{SO_3}$ , the mole fraction of sulfur dioxide in the gas with no conversion, was 0.0642. Since  $K_{SO_3} = 1.07 K_{SO_2}$ , approximately, the value of the group in parentheses in Equation (4) was only about 0.04  $K_{SO_3}$ . This, coupled with the fact that  $K_{SO_3} p G^{-0.49}$  was quite small, made Equation (4) insensitive to changes in mass velocity. Hence, the relationship between  $p_{tSO_3}$  and  $p_{tSO_2}$  is determined by the first two terms of the equation. A similar situation existed with respect to  $p_{tSO_2}$  and  $p_{tSO_3}$ .

The magnitude of the pressure drop due to diffusion resistance is illustrated in Figures 12 and 13, which were prepared from the data in Table 5. Figure 12 shows the effect of temperature and mass velocity upon the ratio of the pressure drop across the film to the pressure in the main gas stream, that is,  $(p_g - p_f)/p_g$ .

As pointed out by Yang and Hougen (5), plots of this type are valuable in determining under what conditions diffusion resistances are important. For example, if the required accuracy in the measurement of reaction rates is 10%, the value of  $(p_g - p_f)/p_g$  should be 0.90 or greater. From Figure 12, this condition would be satisfied at a conversion of 10% provided the temperature were less than about 440° C. at  $G = 514$ , and less than 420° C. at  $G = 147$  lb./hr. (sq.ft.). Figure 13 shows that at 480° C., for the same accuracy, the conversion would have to be greater than 35% at  $G = 514$  and greater than 64% at  $G = 147$  lb./hr. (sq.ft.).

**H.R.U. Approach.** Hurt (7) defined the H.R.U. in terms of the depth of catalyst bed  $h$  and the partial pressure of one of the reactants as follows:

$$\text{H.R.U.} = \frac{h}{-\int_{p_{f1}}^{p_{g2}} \frac{dp_g}{p_g - p^*}}$$
 (7)

where  $p^*$  is the equilibrium value of the partial pressure at the temperature of the reactor. This equation, applied to the differential reactor data obtained in this investigation, becomes

$$\text{H.R.U.} = \frac{h}{\ln \frac{p_{f1} - p^*}{p_{g2} - p^*}}$$
 (8)

Equation (8) was used to evaluate H.R.U. values based upon the partial pressures of sulfur dioxide. The measured conversion at the entrance and exit of the differential catalyst bed permitted the evaluation of  $p_{f1}$  and  $p_{g2}$ . Equilibrium partial pressures  $p^*$  were determined from the following equilibrium equation

$$K = e \left( \frac{22,200}{RT} - \frac{20.96}{R} \right)$$
 (9)

Results are illustrated in Table 6 which includes besides the H.R.U. values of  $p_{f1}/p_g$  at various conversions, temperatures, and mass velocities.

To determine the effect of diffusion on the H.R.U., Hurt proposed a separation into two terms: one, the H.T.U., expressing the resistance to diffusion in the film surrounding the catalyst pellet; and the other, the H.C.U., expressing the resistance due to the processes occurring at the catalyst surface. To

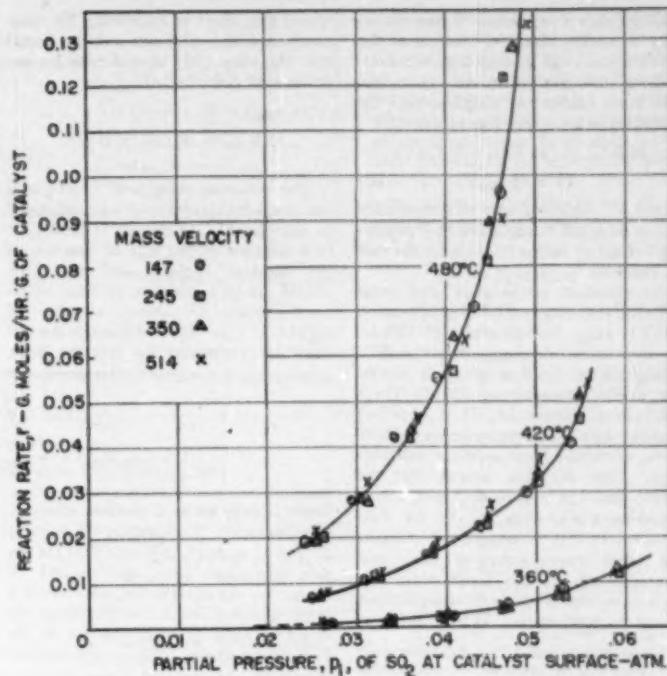


Fig. 11.

TABLE 5  
EQUILIBRIUM PARTIAL PRESSURES

Conversion Percent	G = 147 lb./hr. (sq.ft.) (m³/hr.)				G = 245 lb./hr. (sq.ft.) (m³/hr.)				G = 350 lb./hr. (sq.ft.) (m³/hr.)				G = 514 lb./hr. (sq.ft.) (m³/hr.)			
	$p_g - p_f$	$p_f$	$p_g$	$p_g - p_f$	$p_f$	$p_g$	$p_g - p_f$	$p_f$	$p_g$	$p_g - p_f$	$p_f$	$p_g$	$p_g - p_f$	$p_f$	$p_g$	
10	0.0018	0.0985	0.0001	0.0062	0.0001	0.0000	0.0002	0.0000	0.0004	0.0001	0.0000	0.0000	0.0002	0.0000	0.0000	
20	0.0032	0.0527	0.0004	0.0049	0.0004	0.0035	0.0016	0.0002	0.0027	0.0005	0.0000	0.0000	0.0016	0.0002	0.0000	
30	0.0048	0.0316	0.0006	0.0033	0.0003	0.0000	0.0003	0.0000	0.0005	0.0002	0.0000	0.0000	0.0019	0.0003	0.0000	
40	0.0063	0.0227	0.0008	0.0029	0.0004	0.0000	0.0004	0.0000	0.0006	0.0003	0.0000	0.0000	0.0022	0.0004	0.0000	
50	0.0077	0.0165	0.0010	0.0020	0.0005	0.0000	0.0005	0.0000	0.0007	0.0004	0.0000	0.0000	0.0025	0.0006	0.0000	
60	0.0091	0.0120	0.0012	0.0017	0.0006	0.0000	0.0006	0.0000	0.0008	0.0005	0.0000	0.0000	0.0027	0.0007	0.0000	
70	0.0105	0.0084	0.0014	0.0013	0.0007	0.0000	0.0007	0.0000	0.0009	0.0006	0.0000	0.0000	0.0030	0.0008	0.0000	
80	0.0118	0.0060	0.0016	0.0010	0.0008	0.0000	0.0008	0.0000	0.0010	0.0007	0.0000	0.0000	0.0032	0.0009	0.0000	
90	0.0131	0.0043	0.0018	0.0008	0.0009	0.0000	0.0009	0.0000	0.0011	0.0008	0.0000	0.0000	0.0035	0.0010	0.0000	
100	0.0143	0.0030	0.0020	0.0006	0.0010	0.0000	0.0010	0.0000	0.0012	0.0009	0.0000	0.0000	0.0037	0.0012	0.0000	

Conversion Percent	G = 147 lb./hr. (sq.ft.) (m³/hr.)				G = 245 lb./hr. (sq.ft.) (m³/hr.)				G = 350 lb./hr. (sq.ft.) (m³/hr.)			
	$p_g - p_f$	$p_f$	$p_g$	$p_g - p_f$	$p_f$	$p_g$	$p_g - p_f$	$p_f$	$p_g$	$p_g - p_f$	$p_f$	$p_g$
10	0.0053	0.0987	0.0001	0.0068	0.0001	0.0000	0.0002	0.0000	0.0004	0.0001	0.0000	0.0000
20	0.0053	0.0527	0.0004	0.0049	0.0004	0.0035	0.0016	0.0002	0.0027	0.0005	0.0000	0.0002
30	0.0059	0.0316	0.0006	0.0033	0.0003	0.0000	0.0003	0.0000	0.0005	0.0002	0.0000	0.0003
40	0.0065	0.0227	0.0008	0.0029	0.0005	0.0000	0.0004	0.0000	0.0006	0.0003	0.0000	0.0004
50	0.0071	0.0165	0.0010	0.0013	0.0006	0.0000	0.0005	0.0000	0.0007	0.0004	0.0000	0.0005
60	0.0077	0.0120	0.0012	0.0010	0.0007	0.0000	0.0006	0.0000	0.0008	0.0005	0.0000	0.0006
70	0.0083	0.0084	0.0014	0.0008	0.0008	0.0000	0.0007	0.0000	0.0009	0.0006	0.0000	0.0007
80	0.0089	0.0060	0.0016	0.0006	0.0009	0.0000	0.0008	0.0000	0.0010	0.0007	0.0000	0.0008
90	0.0095	0.0043	0.0018	0.0008	0.0010	0.0000	0.0009	0.0000	0.0011	0.0008	0.0000	0.0009
100	0.0101	0.0030	0.0020	0.0006	0.0007	0.0000	0.0008	0.0000	0.0012	0.0009	0.0000	0.0010

achieve such a separation it was necessary to assume that the reaction at the surface was controlled by a pseudo-first-order mechanism. With this assumption and some additional simplification the following relationship was obtained:

$$H.R.U. = (H.T.U. + H.C.U.) (1 + kp_{SO_3}) \quad (10)$$

where  $k$  is function only of temperature and is designed to represent the "poisoning" effect of sulfur trioxide on the rate of reaction.

At constant temperature and mass velocity the only variable in Equation (10) is  $p_{SO_3}$ . Hence, a plot of H.R.U. vs. conversion, or  $p_{SO_3}$ , should yield a straight line. Such a graph is shown for a mass velocity of 350 lb./hr. (sq.ft.) in Figure 14. It is observed that the data at all temperatures indicate some deviation from a linear relationship. This deviation means that the single constant pseudo first order, rate Equation (10), does not fit the data obtained in this investigation. Graphs for other mass velocities are similar, although at the lower mass velocities the deviation from straight lines is not as pronounced. It may be men-

tioned that Hurt in examining the same reaction with a platinum catalyst found that Equation (10) agreed with his experimental information

$$H.R.U. = H.T.U. (1 + kp_{SO_3})^n + H.C.U. (1 + kp_{SO_3})^n \quad (10a)$$

This equation contains two constants,  $k$  and  $n$ , which must be evaluated from experimental information. Data obtained in this investigation are correlated better by Equation (10a) than (10) as would be expected from the additional latitude permitted by the two-constant equation.

tioned that Hurt in examining the same reaction with a platinum catalyst found that Equation (10) agreed with his experimental information

$$At p_{SO_3} = 0, \quad H.R.U. = H.T.U. + H.C.U. \quad (11)$$

This equation along with Hurt's data for mass-transfer rates was employed to calculate H.C.U. values. The H.C.U. is a measure of the rate of reaction at the catalyst surface, and therefore, should not be a function of mass velocity. Figure 15 shows a plot of  $\ln(H.C.U.)$  vs.  $1/T$ . Although the results are correlated by straight lines,

were studied to make a thorough study of the controlling mechanism for the reaction at the catalyst surface. However, various mechanisms leading to expressions for the rate, have been proposed for this reaction (2, 8, 9), and the data presented in this paper can be used to check these earlier proposals. The most fundamental approach appears to be that of Uehara and Watson (9) who used the data of Lewis and Ries to test various mechanisms. Their analysis indicated that the most likely rate-controlling step in the over-all process at the catalyst surface was the reaction between adsorbed sulfur dioxide and adsorbed atomic oxygen. The rate equation corresponding to this case is

$$r = \frac{E_A C T e^{-\frac{\Delta H^*}{RT}} \left( p_{SO_2} p_{O_2} - \frac{p_{SO_3}}{K} \right)}{\left[ 1 + (p_{O_2} K_{O_2})^{\frac{1}{2}} + p_{SO_2} K_{SO_2} + p_{SO_3} K_{SO_3} + p_{N_2} K_{N_2} \right]^2} \quad (12)$$

there is seen to be a distinct effect of mass velocity. Comparison of Figures 10 and 11 with 15, indicates that for the data presented here, the method of evaluating surface partial pressures is a more accurate means of handling the effect of diffusion than the use of the H.R.U. approach. This is not entirely unexpected in view of the assumption regarding reaction mechanism that is necessary in applying the latter scheme.

**Reaction Mechanism.** As stated earlier, insufficient composition variables

and the following equations apply at the catalyst surface, i.e., they are  $p_i$  values. At a fixed temperature all the adsorption coefficients are constant as well as the group

$$E_A C T e^{-\frac{\Delta H^*}{RT}} \text{ (designated as } C_T^2 \text{)}$$

Also the partial pressure of nitrogen was essentially constant so that its effect may be neglected. Hence, Equation (12) may be rearranged in the following way, in which the only variables are  $p_{SO_2}$ ,  $p_{O_2}$ , and  $p_{SO_3}$ :

$$\left[ \frac{p_{SO_2} p_{O_2}^{\frac{1}{2}} - \frac{p_{SO_3}}{K}}{r} \right]^{\frac{1}{2}} = \frac{1}{C_T^2} [1 + p_{SO_2} K_{SO_2} + p_{O_2}^{\frac{1}{2}} K_{O_2}^{\frac{1}{2}} + p_{SO_3} K_{SO_3}] \quad (13)$$

Because the only composition variable studied in this investigation was conversion, there existed a relationship between  $p_{SO_2}$ ,  $p_{SO_3}$  and  $p_{O_2}$ . Therefore, Equation (13) can be written,

$$R = B + D p_{SO_3}, \quad (14)$$

where

$$R = \left[ \frac{p_{SO_2} p_{O_2}^{\frac{1}{2}} - \frac{p_{SO_3}}{K}}{r} \right]^{\frac{1}{2}}$$

and  $B$  and  $D$  are constant at a fixed temperature. Equation (14) is linear in form, and the constants  $B$  and  $D$  can be evaluated by the method of least squares. The experimental data necessary are the rate and  $p_i$  values given in Table 5 and shown for  $SO_2$  and  $SO_3$  in Figures 10 and 11. Values of  $B$  and  $D$  so determined at various temperatures are shown in Table 7.

The fact that the values of  $B$  and  $D$  in Table 7 are all positive indicates that the proposed mechanism gives a satisfactory interpretation for the rate data

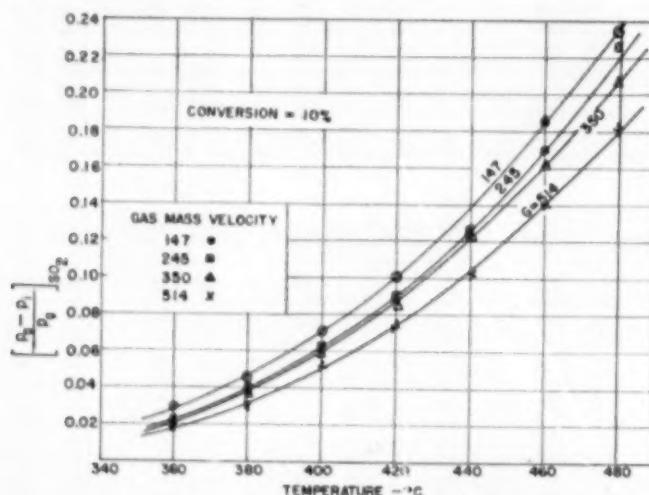


Fig. 12. Effect of temperature upon film pressure drop.

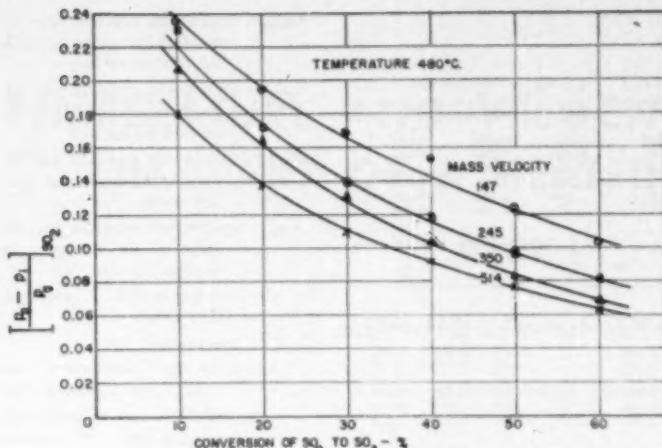


Fig. 13. Effect of conversion upon film pressure drop.

of this investigation. Positive values are a requirement because of the necessity that the adsorption coefficients in Equation (12) be greater than zero. Equation (14) is compared with the experimental rate data in Figure 16 at three temperatures. The agreement of the data with the straight line relationship is reasonably good in each case.

Five other proposed mechanisms were analyzed in the same manner. These were as follows:

1. Surface rate controlling: adsorbed atomic oxygen and sulfur dioxide in the gas phase
2. Surface rate controlling: adsorbed sulfur dioxide and molecular oxygen in the gas stream
3. Adsorption of sulfur dioxide controlling the reaction between adsorbed atomic oxygen and sulfur dioxide
4. Adsorption of oxygen controlling the reaction between adsorbed atomic oxygen and sulfur dioxide
5. Desorption of sulfur trioxide controlling the rate between adsorbed atomic oxygen and sulfur dioxide

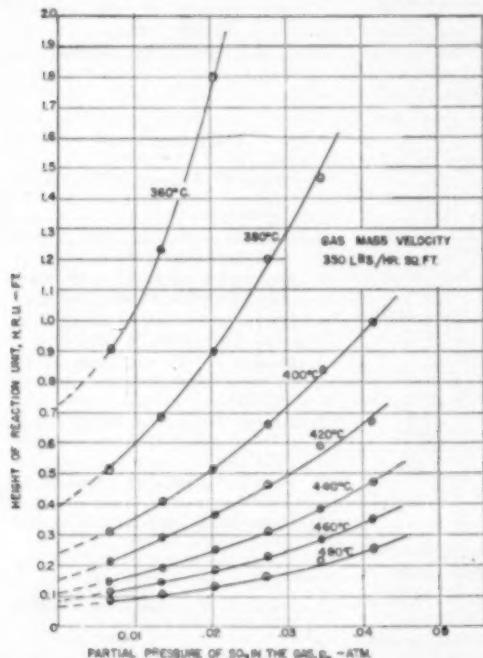


Fig. 14.

Results of these analyses showed that both mechanisms (1) and (2) were acceptable and correlated the experimental data in tests similar to Figure 16, but (3), (4) and (5) led to negative adsorption coefficients. In summary, any of the mechanisms based upon surface reaction rate as the controlling feature was satisfactory, while those based upon adsorption or desorption as controlling were unsatisfactory.

#### Notation

$a$  = catalyst area per unit mass, lb./sq.ft.

$B, D$  = constants (at a fixed temperature) in surface reaction rate equation. Defined by Equations (13) and (14)

$C_F^0$  = over-all rate constant in kinetic equations

$$D = C_F^0 = E_A C T e^{-\frac{\Delta H^0}{RT}}$$

a constant at a fixed temperature

$D$  = diffusivity of a single component in gas mixture, sq. ft./sec.

$d_p$  = effective diameter of catalyst  
 $= (1.5)^{1/6}$  (diameter of cylindrical catalyst pellet)

$E_A$  = effectiveness factor of catalyst. Constant for a given catalyst

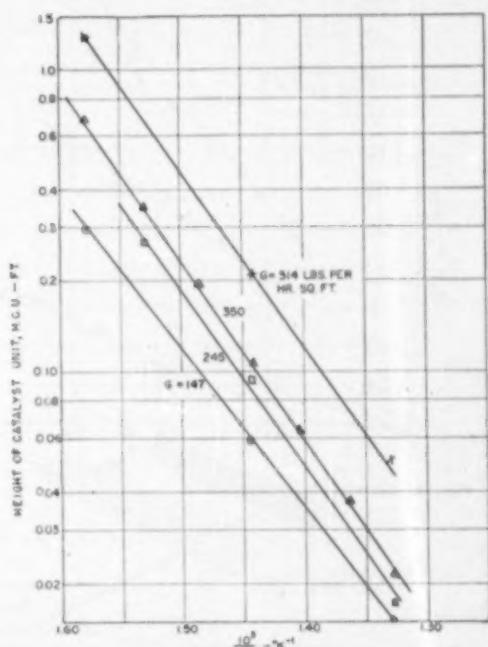


Fig. 15. H. C. U. vs. temperature.

TABLE 6  
H.R.U. Values

Conversion Percent	$P_{SO_3}$ Atm.	$G = 147 \text{ lbs.}/(\text{hr.})(\text{sq.ft.})$		$G = 215 \text{ lbs.}/(\text{hr.})(\text{sq.ft.})$	
		$360^\circ \text{C}$	$420^\circ \text{C}$	$360^\circ \text{C}$	$420^\circ \text{C}$
10	0.0064	0.375	0.103	0.407	0.170
20	0.0131	0.437	0.127	0.526	0.219
30	0.0198	0.730	0.153	0.684	0.261
40	0.0267	0.934	0.179	0.835	0.309
50	0.0336	1.19	0.215	1.03	0.360
60	0.0406	2.22	0.282	1.17	0.386

$G = 350 \text{ lbs.}/(\text{hr.})(\text{sq.ft.})$		$H_R = f_1$					
Conversion Percent	$P_{SO_3}$ Atm.	$360^\circ \text{C}$	$380^\circ \text{C}$	$400^\circ \text{C}$	$420^\circ \text{C}$	$440^\circ \text{C}$	$460^\circ \text{C}$
10	0.0064	0.907	0.512	0.308	0.212	0.167	0.110
20	0.0131	1.22	0.681	0.407	0.292	0.193	0.142
30	0.0198	1.79	0.896	0.512	0.356	0.242	0.181
40	0.0267	2.59	1.20	0.646	0.462	0.308	0.224
50	0.0336	3.38	1.47	0.838	0.693	0.576	0.477
60	0.0406	—	—	0.99	0.667	0.470	0.344

$G = 514 \text{ lbs.}/(\text{hr.})(\text{sq.ft.})$		$H_R = f_1$					
Conversion Percent	$P_{SO_3}$ Atm.	$360^\circ \text{C}$	$380^\circ \text{C}$	$400^\circ \text{C}$	$420^\circ \text{C}$	$440^\circ \text{C}$	$460^\circ \text{C}$
10	0.0064	1.55	0.997	0.522	—	—	—
20	0.0131	2.25	0.981	0.553	—	—	—
30	0.0198	3.44	0.858	0.590	—	—	—
40	0.0267	6.24	0.564	0.231	—	—	—
50	0.0336	—	0.738	0.237	—	—	—
60	0.0406	—	0.978	0.317	—	—	—

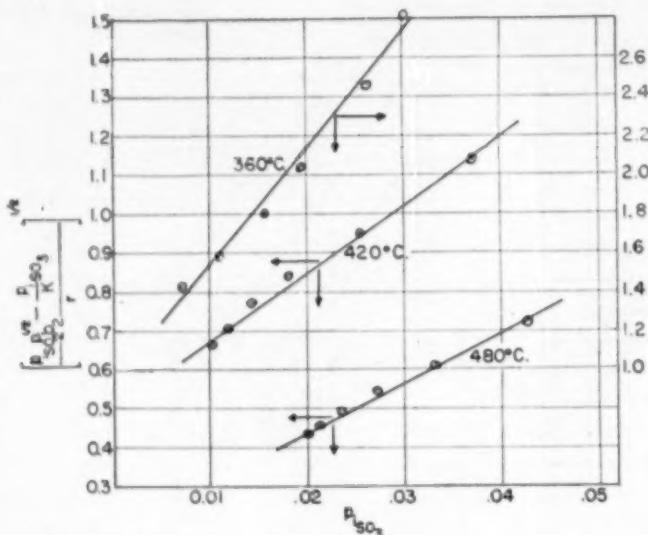


Fig. 16. Correlation of rate data. ▲

TABLE 7.—RATE CONSTANTS FOR EQUATION (18)

Temperature °C.	$R$	$D$
360	0.906	61.6
420	0.499	17.5
480	0.176	12.9

$G$  = gas mass velocity, lb./hr. (sq.ft. of empty reactor)

$\Delta H^\circ$  = over-all standard enthalpy change for reaction

$K$  = equilibrium constant for over-all oxidation of sulfur dioxide

$K_{SO_3}$  = equilibrium constant for adsorption of sulfur dioxide on catalyst surface

$K_{SO_3}$  = equilibrium constant for adsorption of sulfur trioxide on catalyst surface

$K_{O_2}$  = equilibrium constant for adsorption of oxygen on catalyst surface

$K_{N_2}$  = equilibrium constant for adsorption of nitrogen on catalyst surface

$n$  = constant in H.R.U. rate equation (10a)

$T$  = temperature, °K.

$k$  = poisoning coefficient in H.R.U. rate Equation (10)

$P_g$  = partial pressure, in main body of gas, atm.;  $P^*$  = equilibrium partial pressure

$P_t$  = partial pressure at catalyst-gas interface, atm.

$P_f$  = pressure film factor, atm.

$P$  = total pressure, atm.

$r$  = over-all reaction rate, gram moles of sulfur dioxide converted per hour per gram of catalyst.  $r_\infty$  rate at infinite mass velocity

$X_0$  = mole fraction of sulfur dioxide in unconverted reaction mixture = 0.0642

$\mu$  = viscosity of gas mixture, lb./hr. (ft.)

$\rho$  = density of gas mixture, lb./cu.ft.)

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# TEMPERATURE AND VELOCITY DISTRIBUTION IN WAKE OF A HEATED CYLINDER<sup>†</sup>

## PART I

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Detailed measurements have been made of the temperature and velocity distributions in the wake of a heated cylinder. The cylinder which was 12.15 in. long and 0.190 in. in diameter was placed midway between the upper and lower parallel walls of a conduit of rectangular cross section through which air flowed normal to the cylinder. The temperature of the walls of the conduit was maintained identical to the bulk temperature of the entering air. Energy dissipation from the cylinder was kept at a uniform value of 4460 B.t.u./hr. (sq.ft.) for measurements at Reynolds numbers of 562, 1221, 2285, and 4440 based on the diameter of the cylinder. Point values of temperature and air speed were determined as a function of position in the wake of the cylinder. These data were obtained in sufficient detail to permit the calculation of eddy viscosity and eddy conductivity. Results are presented in tabular form, and several graphical representations of the data have been included.

THE velocity distribution in the wakes of cylinders has been the subject of a number of investigations (2, 3, 8, 11, 13, 14) in which it was assumed that isothermal conditions prevailed. In addition some investigations have been made of the temperature distribution in the vicinity of a heated cylinder (3, 7, 9, 15). However, none of these data served to establish in detail the variations in both air temperature and speed in the wake of a heated cylinder. This information is of particular interest in establishing the utility of the Reynolds analogy (16) in predicting temperature gradients when the air speed profiles and the requisite boundary conditions are established. However, in order to determine with certainty the quantitative relationship between eddy conductivity and eddy viscosity (4, 16, 17) for the relatively complex situations obtaining in the wake of a heated cylinder, detailed air temperature and speed profiles are required. In the present investiga-

tion detailed information concerning such temperature and air speed profiles was obtained for four sets of conditions. Values of eddy conductivity and

eddy viscosity based upon these data will be presented as a separate paper.

Present measurements involved the determination of point values of air temperature and speed in a substantially two-dimensional air stream in the wake of a heated cylinder 0.190 in. in diameter. The heated cylinder was positioned normal to the flow, approximately 6 ft. from the entrance to the conduit and midway between the walls which were separated by a distance of 0.75 in. Suitable traversing equipment was employed to permit the careful establishment of the location of a hot wire anemometer and a pitot tube shown in Figure 1. The pitot tube was used to calibrate the hot wire anemometer as a speed-measuring device. The 0.5-mil platinum wire was

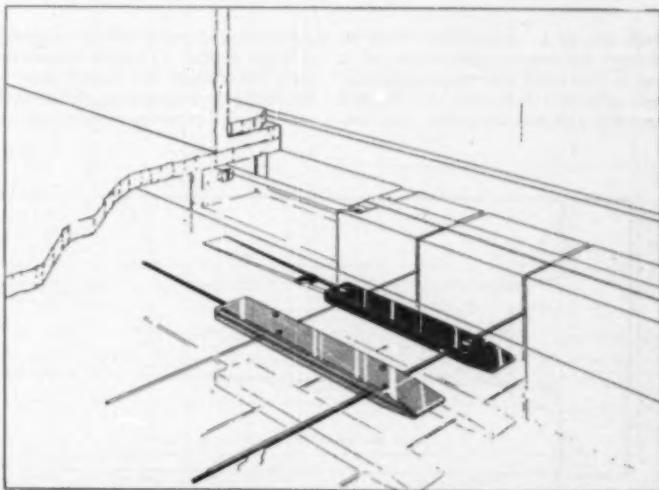


Fig. 1. Pitot tube and hot wire anemometer.

<sup>†</sup> This paper is a short version of a paper on file with the American Documentation Institute (Document 2921), 1719 N St., N.W., Washington, D. C. Obtainable by remitting 70 cents for a microfilm and \$7.00 for photocopies.

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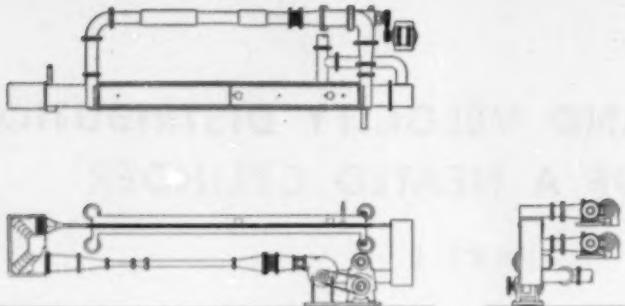


Fig. 2. General layout of apparatus.

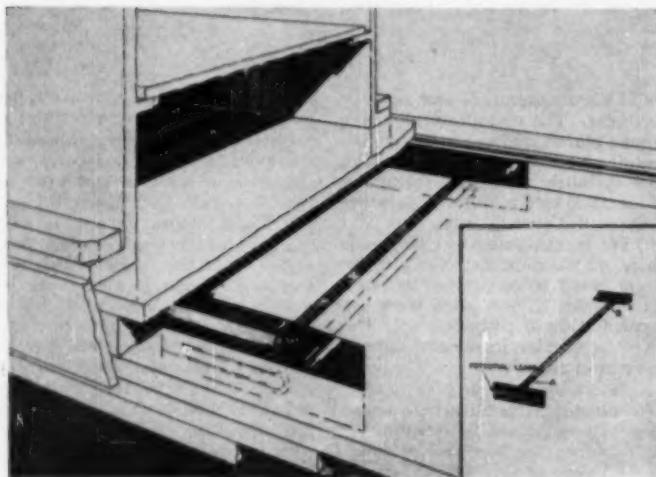


Fig. 3. Stainless steel heated cylinder mounted in the channel.

used also as a conventional 4-lead resistance thermometer, and because of its use in both speed and temperature measurements, this instrument hereafter will be called a thermanemometer. Air tem-

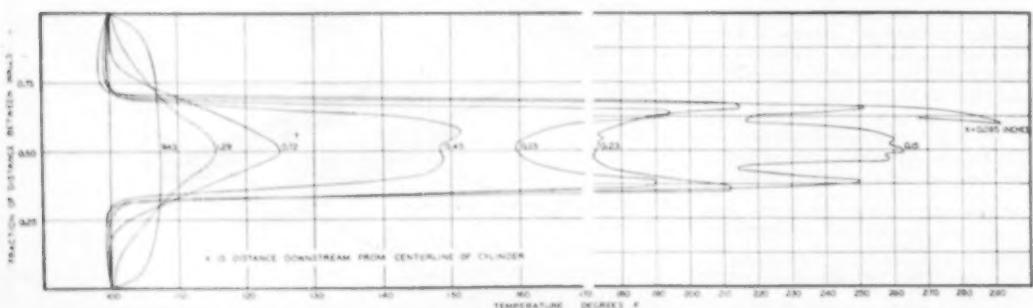
peratures and speeds were determined at a large number of points downstream from the cylinder in a vertical plane intersecting the longitudinal midline of the cylinder. The studies were carried out

at bulk air velocities of approximately 6.99, 12.7, 24.8, and 44.7 ft./sec., which correspond to Reynolds numbers of 562, 1221, 2285, and 4440 based on the diameter of the cylinder. A rate of thermal dissipation of energy from the cylinder of 4460 B.t.u./hr. (sq.ft.) corresponding to 5.42 watts/lin.in. of the cylinder was maintained at each Reynolds number.

**Equipment.** It is not proposed to describe in detail all the equipment employed since the general features of the apparatus will be covered in a separate contribution dealing with temperature gradients in uniform, two-dimensional turbulently flowing air streams. The equipment was designed on the basis of experience gained in the construction and operation of apparatus which was described earlier (6).

In principle, the equipment involved a closed flow channel so arranged that air of a predetermined temperature and a nearly uniform velocity was supplied to a working section 13 ft. in length, 0.75 in. in height, and 12 in. in width. The general arrangement is shown in Figure 2. In contradistinction to the earlier design (6), the side walls of the conduit were movable and thus permitted vertical traverses to be carried out at any number of positions along the conduit rather than at only the one section possible with the original equipment. In addition, the traversing equipment has been refined to permit the vertical positioning of the thermanemometer to within 0.001 in.

The temperature of the upper and lower copper plates, which comprised the top and bottom of the conduit, was maintained within  $0.02^{\circ}$  F. of a predetermined value by means of oil circulating external to the plates. Substantially uniform turbulent flow was developed in the conduit of the dimensions indicated, and the air entered the section at the same temperature as the walls. Figure 3 shows the general arrangement of the heated cylinder in the working section. In an insert to this schematic diagram the details of construction of the cylinder are presented. The cylinder consisted of a stainless steel tube 0.190 in. O.D. and 0.170 in. I.D. The electric resistance of this tube was 0.006190 ohm/in. at  $210.4^{\circ}$  F. and 0.005670 at  $100.0^{\circ}$  F. In or-



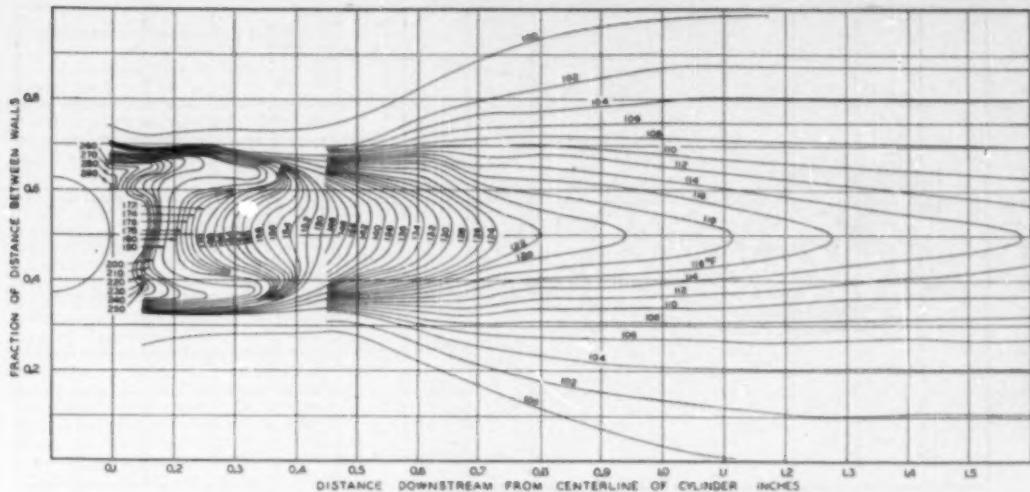


Fig. 5. Temperature field in wake of steel cylinder at bulk air velocity of 6.99 ft./sec.

der that the energy dissipation per unit length near the center of the channel could be determined, potential leads were connected to contact rings located on the interior of the tube as indicated at *A* and *B* in the insert to Figure 3. These contact rings were soldered to the inside of the tube in order to obtain a relatively accurate evaluation of the differences of potential between the two points.

The average temperature of the cylinder was established from the measurement of the resistance of the tube between the two

potential rings. As a function of temperature at negligible rates of energy dissipation the electric resistance of the tube was determined when the tube was immersed in an agitated liquid bath at a series of known temperatures. Reproducible values were obtained for the calibration before and after the tube had been subjected to relatively high rates of energy dissipation. The average temperature of the tube could be established with an uncertainty of approximately 0.5° F. However, it is desired to emphasize the fact that this average tem-

perature does not yield information as to the temperature distribution on the surface of the cylinder.

In order to estimate the distribution of the surface temperature a cylinder of somewhat more complicated construction was employed. This cylinder consisted of a brass tube which had been parted longitudinally and within which was placed a nichrome wire heater. The over-all dimensions of this brass tube were the same as the dimensions of the steel tube. Fourteen copper-constantan thermocouples were

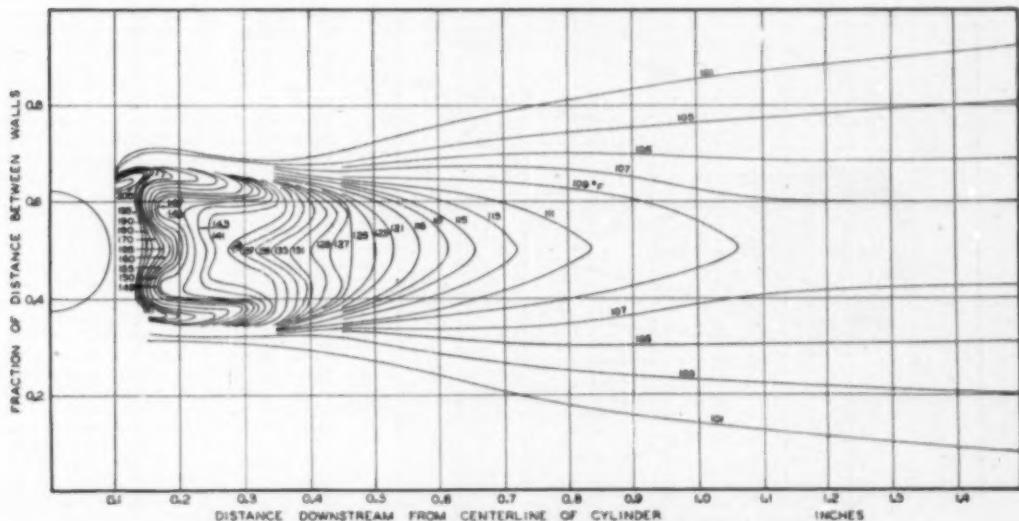


Fig. 6. Temperature field in wake of steel cylinder at bulk air velocity of 12.7 ft./sec.

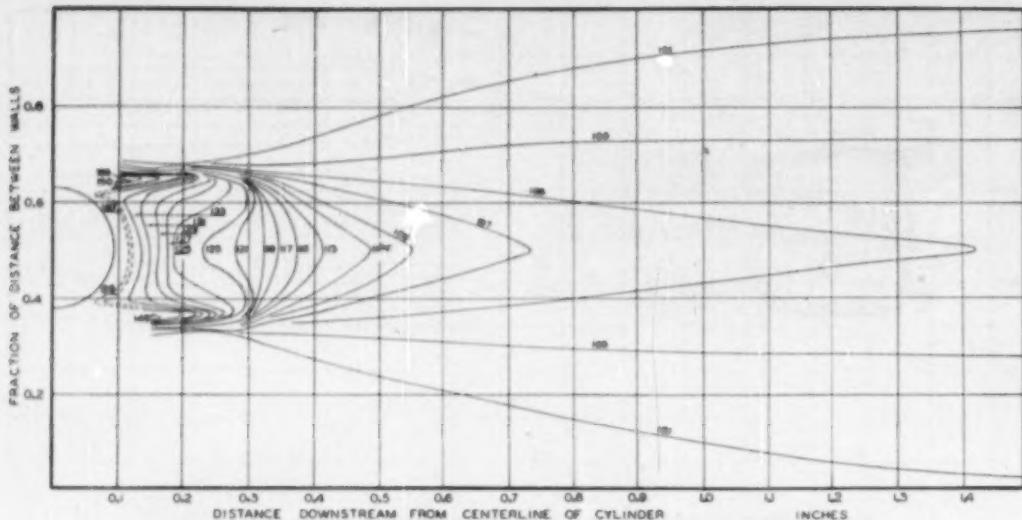


Fig. 7. Temperature field in wake of steel cylinder at bulk air velocity of 24.8 ft./sec.

bedded in the walls of the brass tube. They were insulated electrically from the walls of the brass tube by means of a thin plastic coating. Potential leads to determine the rate of energy addition to the heater were connected to the nichrome wire heater within the tube. The current and potential leads were brought out of both ends of the tube. This particular design suffered from the difficulty of unsymmetrical heating of the tube and the associated uncertainty of the longitudinal tem-

perature distribution. However, with this arrangement, it was possible to obtain rough estimates of the circumferential variation in temperature as well as of the average surface temperature for a particular over-all rate of energy dissipation. The brass tube was used in a limited number of measurements made early in the program. However, because of the difficulty just mentioned, this design was discarded for the simpler arrangement involving the use of the stainless steel tube. In the latter

instance it was possible to determine only the average temperature of the metal wall of the tube, and so no data concerning the longitudinal, radial, or circumferential temperature distribution were available for the measurements with the stainless steel tube.

A recently calibrated type *K*-2 potentiometer was employed to measure the potential across the stainless steel cylinder or across the heater within the brass cylinder. This device was used also to measure the

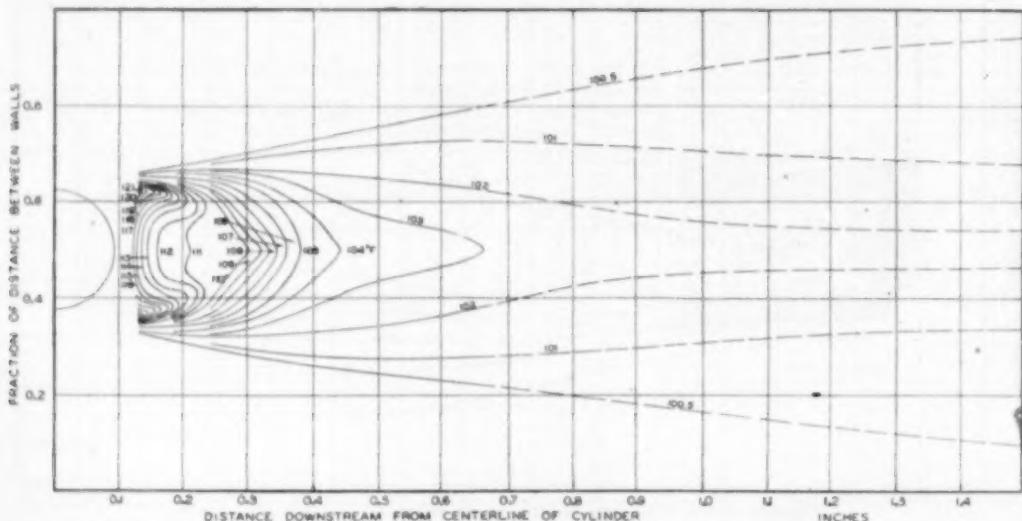


Fig. 8. Temperature field in wake of steel cylinder at bulk air velocity of 44.7 ft./sec.

current flowing through the cylinder. A White double potentiometer was employed for measurements of temperature on the external surface of the brass tube with the small copper-constantan thermocouples. Mueller-type bridges were utilized in measuring the bulk temperature of the air stream entering the conduit and the temperature of the oil flowing outside the upper and lower copper surfaces of the conduit. The air and oil streams were maintained at a constant temperature by electronic control circuits. A type K-2 potentiometer was used in the measurements required for the determination of the air speed with the thermancrometer. A Mueller-type bridge was used to measure the point temperature.

The circuit employed in connection with the thermancrometer was arranged to permit its use as a device for measuring both temperature and air speed. In the measurement of the temperature of the flowing stream the wire was used as a conventional 4-lead resistance thermometer the resistance of which was evaluated within 0.01%. The influence of air speed on the free stream temperature measurements was taken into account by means of an impact temperature correction which was employed at air speeds in excess of 40 ft./sec. At 60 ft./sec. this correction amounted to  $-0.04^{\circ}\text{F}$ . In the case of the air speed measurements, the constant resistance method of hot wire anemometry was employed (18), and the temperature of the wire was maintained at a constant temperature of about  $200^{\circ}\text{F}$ . as indicated by a fixed electric resistance. The current flowing through the wire required to bring it to this predetermined temperature was a function of the air speed and temperature of the air flowing past the wire (18).

The hot wire anemometer was calibrated under isothermal conditions with a vertical traversing pitot tube of conventional design (10). The calibration corresponded satisfactorily with that predicted from theory (18). The error in speed measurements due to the frequency and amplitude of fluctuating velocities (8) is believed to be negligible in portions of the wake some distance downstream of the cylinder. However, in regions of the wake close to the cylinder where the Kármán vortex trails (10) are encountered, the high amplitudes and frequencies of the velocity fluctuations cause inaccuracies in the speed measurements. It is emphasized that the anemometry used in this investigation did not establish the vectorial characteristics of the velocity in the wake of the cylinder and thus all such data have been submitted in terms of air speed rather than velocity. Mean values of temperature and mean air speed were recorded in regions of the wake where velocity fluctuations of large amplitude were encountered. It is believed that the air speed in portions of the wake downstream from the cylinder was determined within 0.5 ft./sec. or 1%, whichever is the larger. In portions of the wake where the vortex trails are present errors as large as 15% may have occurred in the air speed measurements. From a consideration of the uncertainties in the temperature measurements including those associated with the evaluation of the influence of the impact temperature upon the measurements, it is believed that the temperature

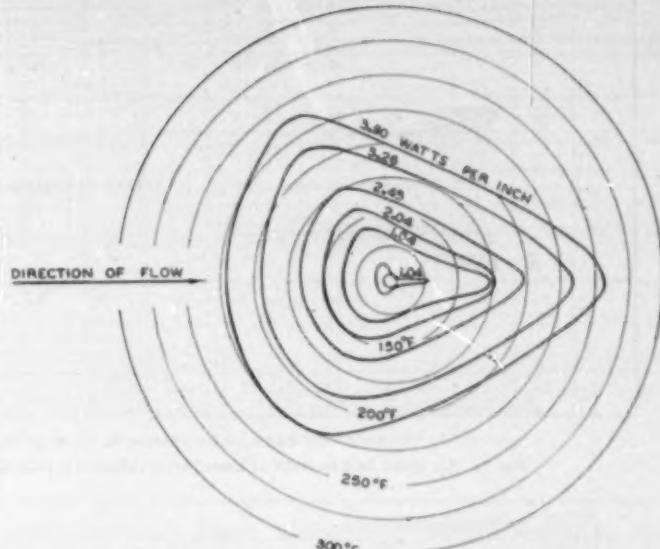


Fig. 9. Estimated circumferential temperature distribution on surface of brass cylinder at bulk air velocity of 14.4 ft./sec.

of the flowing gas was established with an uncertainty of approximately  $0.1^{\circ}\text{F}$ . For air speeds in excess of 40 ft./sec. the uncertainty may be as large as  $0.2^{\circ}\text{F}$ . The influence of air speed upon the temperature determinations was established by careful measurements of apparent temperature as a function of air speed under isothermal conditions.

**Methods.** In the present measurements, the air stream and the upper and lower walls of the working section were brought first to a temperature of  $100.0^{\circ}\text{F}$ . This temperature was maintained for a sufficient period to insure that steady conditions had been reached. At various bulk air speeds the thermancrometer was calibrated as a speed-measuring device. The speed calibra-

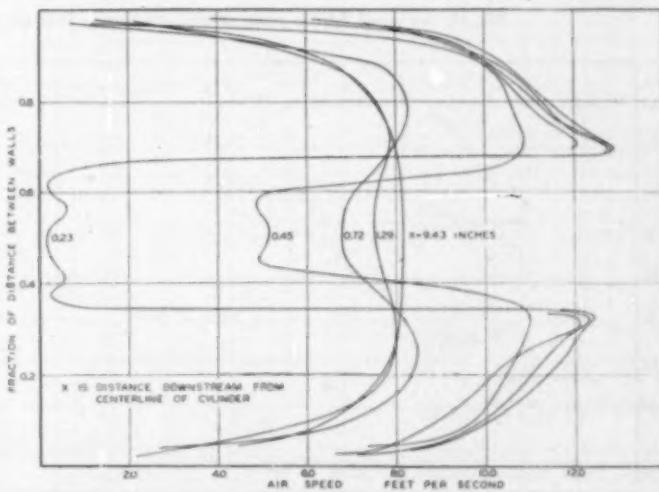
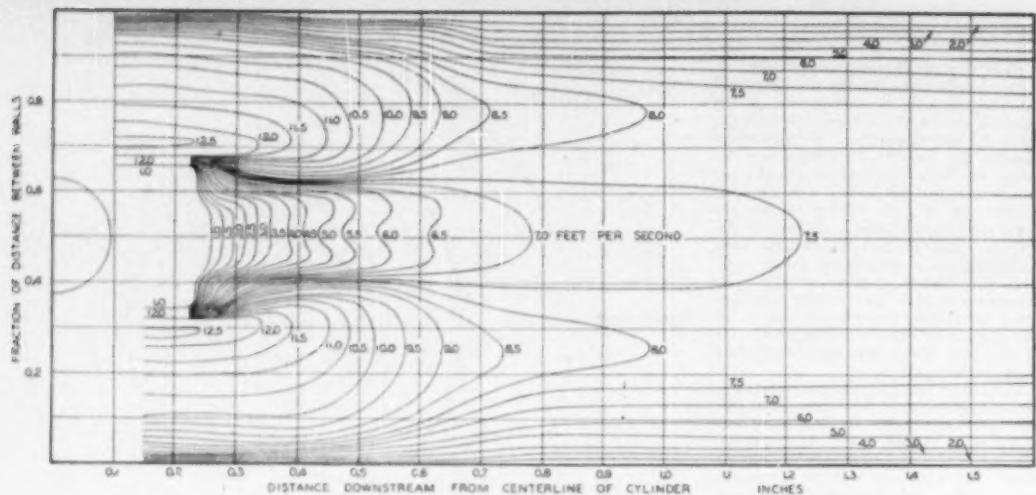


Fig. 10. Air speed distribution in wake of steel cylinder at bulk air velocity of 6.99 ft./sec.



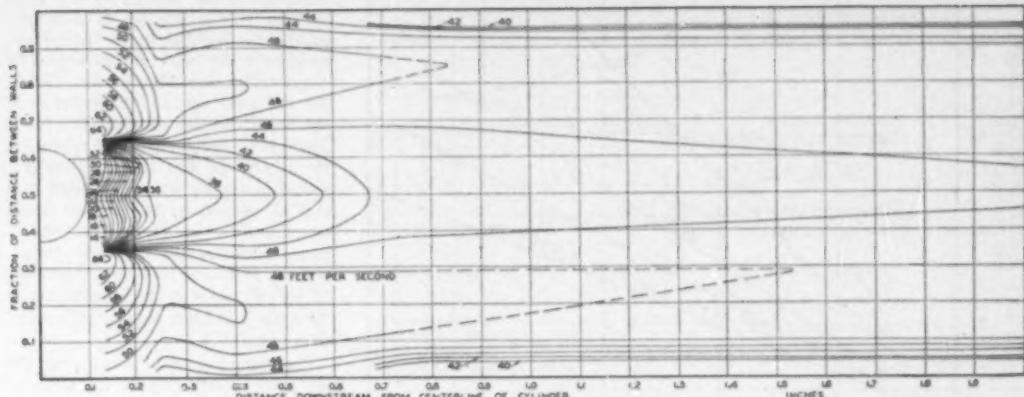


Fig. 14. Air speed field in wake of steel cylinder at bulk air velocity of 44.7 ft/sec.

tions were made at 8-hr. intervals in order to detect any changes in behavior with time which were found to be appreciable. Energy was then added to the cylinder at a rate of 5.42 watts/in. of length of the tube, which was the arbitrarily chosen fixed rate of energy dissipation utilized throughout the present set of measurements. Traverses were then made at a suitable number of different longitudinal positions downstream from the cylinder. At each position the temperature and air speed were determined at approximately 20 different elevations between the upper and lower plates. Check measurements were made at several longitudinal positions and it was found that the temperature and air speed distribution agreed with the original traverse within the indicated limits of error. This reproducibility serves to indicate that steady conditions were obtained and maintained within the uncertainty of the temperature and air speed measurements.

### Results

Detailed tabular results of the investigation at Reynolds numbers of 562, 1221, 2285, and 4440 are available (1). These Reynolds numbers, which are based on the dimensions of the cylinder, correspond to bulk velocities of 6.99, 12.7, 24.8, and 44.7 ft/sec. For each location in the wake of the steel cylinder the air speed and air temperature are recorded. The nature of the measurements with the thermistor was such that the vector velocity was not measured. It appears that the accuracy of the data is relatively uniform and equivalent to the limitations in both temperature and air speed measurements described in an earlier part of this discussion.

For a gross air velocity of 6.99 ft/sec. the temperature and air speed distribution have been presented in two

different fashions. In Figure 4 the temperature is presented as a function of elevation for several different points downstream from the centerline of the cylinder. The same data are presented in Figure 5 in terms of lines of constant temperature. These diagrams indicate relatively complex temperature profiles, and the occurrence of a high temperature region is clearly evident in the wake downstream from the upper and lower edges of the cylinder. It is per-

haps of interest to note that at a distance of 0.15 in. downstream from the centerline of the cylinder and opposite the upper edge, a temperature of 250.8° F. was reached. The corresponding value of temperature on the lower part of the cylinder was 249.7° F. This lack of symmetry is evident in the case of all traverses near the cylinder at a gross air velocity of 6.99 ft/sec. and probably can be explained by natural convection which would be particularly effective at

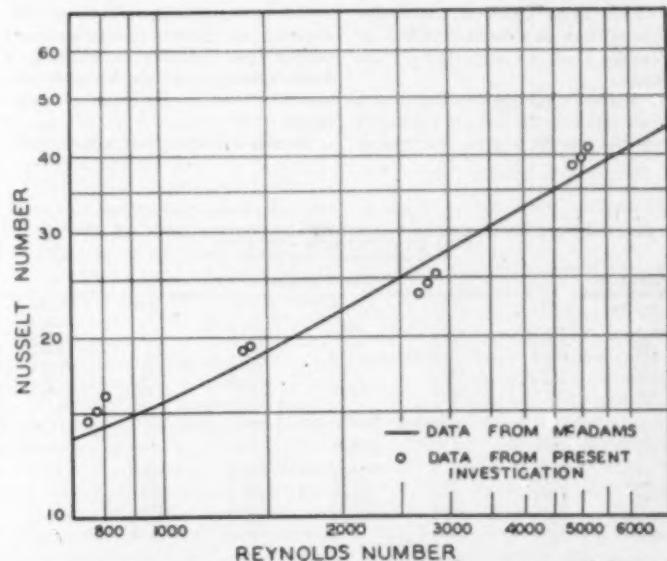


Fig. 15. Correlation of thermal energy transfer data for heated cylinder.

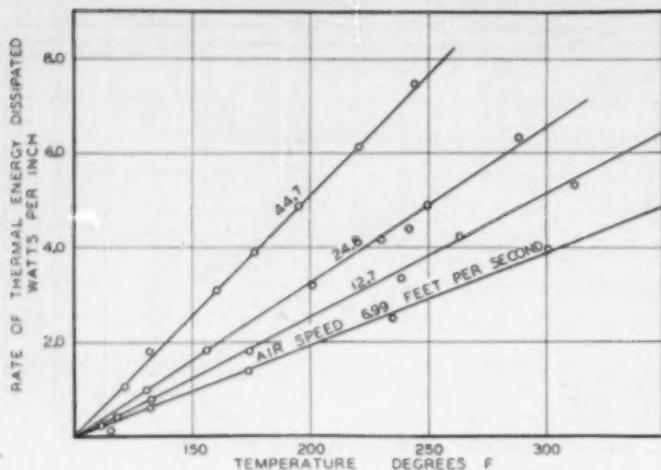


Fig. 16. Thermal energy transfer as a function of average surface temperature of steel cylinder.

the lower velocities.

The corresponding temperature fields for gross velocities of 12.7 and 24.8 ft./sec. are shown in Figures 6 and 7. In these instances the lack of symmetry as a result of natural convection is again evident. Figure 8 portrays the temperature field at a bulk velocity of 44.7 ft./sec. In this instance the effect of natural convection has been obscured within the precision of the existing measurements. A maximum temperature of 114.2° F. was found at the upper and lower sides of the cylinder at a distance of 0.19 in. downstream of the centerline of the cylinder.

A detailed tabulation of temperatures and air speeds in the wake of the heated brass cylinder for a gross air velocity

of 14.4 ft./sec. is available (1). These data are not considered as accurate as those reported for the stainless steel cylinder as a result of the nonuniform heating of the brass cylinder. For this reason it is estimated that the uncertainties in temperature measurements are at least twice those indicated in the earlier part of this report while the uncertainties in the air speed measurements may be as much as three times the uncertainties associated with the steel cylinder measurements. This larger uncertainty in the case of the air speed results from difficulty in obtaining a stable calibration of the hot wire anemometer used in the early measurements.

By means of the small thermocouples

TABLE I.—CIRCUMFERENTIAL TEMPERATURE DISTRIBUTION ON SURFACE OF A HEATED BRASS CYLINDER  
Bulk Air Velocity 14.4 ft./sec.

Position on Nomenclature Degrees	Wattage Dissipation watts/in.				
	1.04	1.64	2.04	2.45	3.26
0	127.6	172.8	176.4	198.0	254.1
60	106.0	137.1	136.7	153.3	179.7
120	111.7	134.8	145.4	164.8	195.6
180	110.5	134.7	145.4	165.8	195.2
240	116.4	142.1	158.6	176.0	209.3
300	103.1	138.0	139.8	165.7	180.5
Bulk Air Velocity 33.8 ft./sec.					
	1.82	1.71	2.44	3.13	4.08
0	129.6	146.4	173.6	199.3	232.0
60	106.7	134.0	130.0	146.1	175.8
120	110.8	131.1	136.9	162.6	192.0
180	110.1	132.0	144.0	163.8	192.0
240	118.0	124.4	137.2	179.3	213.1
300	103.2	114.5	139.7	145.5	159.1

\* Temperature in ° F  
 ? Points on circumference are designated by polar angles, 0° represents the trailing edge of the cylinder; 90° represents upper, *i.e.*, *of*, cylinder.

imbedded in the surface of the brass cylinder it was possible to determine roughly the variation in the surface temperature of the brass cylinder around its circumference. In Figure 9 and Table 1 the indicated surface temperatures of the brass cylinder are presented as a function of angular position relative to the axis of the flow stream. Data presented in Figure 9 were obtained at a bulk air velocity of 14.4 ft./sec. These measurements were obtained, as were all other measurements reported herein, with an incoming bulk air temperature of 100° F. and with the temperature of the upper and lower copper walls maintained at 100° F.

Corresponding data concerning the air speed distribution in the wake of the steel cylinder are presented in Figures 10 to 14, inclusive, Figure 10 portrays the air speed distribution for a bulk velocity of 6.99 ft./sec. on the basis of the variation in speed at fixed distances downstream from the center-line of the heated cylinder, and Figures 11 to 14 by means of lines of constant speed for each of the four different gross air velocities used in these studies.

Various rates of thermal transfer of energy from the cylinder have been obtained at gross air velocities of 6.99, 12.7, 24.8, and 44.7 ft./sec. These data have been correlated in the form of a dimensionless parameter involving the logarithm of the Nusselt number and the logarithm of the Reynolds number. These data are presented in Figure 15 along with similar results of other investigations (12). There is good agreement between the data of this investigation and those already available in the literature.

Figure 16 and Table 2 show data as to the rate of thermal transfer of energy as a function of average surface temper-

TABLE 2.—THERMAL ENERGY TRANSPER  
AS A FUNCTION OF AVERAGE SURFACE  
TEMPERATURE OF CYLINDER

Watts/in. in Dissipated	Average Surface Temper- ature ° F.	Watts/in. in Dissipated	Average Surface Temper- ature ° F.
Bulk Air Velocity 6.99 ft./sec.		Bulk Air Velocity 24.8 ft./sec.	
0.089	115.0	0.946	131.6
0.576	132.3	1.799	154.8
1.365	173.8	3.209	201.3
2.504	235.2	4.141	232.0
3.972	301.3	4.383	241.3
6.395	409.2		
Bulk Air Velocity 13.7 ft./sec.		Bulk Air Velocity 44.7 ft./sec.	
0.226	113.0	1.029	131.5
0.439	114.0	3.078	160.6
0.782	132.8	3.983	176.3
1.815	174.8	4.875	195.3
3.247	238.8	6.147	220.8
4.229	283.4	7.439	244.2
5.424	310.0		
7.731	342.5		

ature for gross air speeds of 6.99, 12.7, 24.8, and 44.7 ft./sec. Over the range of temperatures thus far investigated a linear relation exists between the rate of thermal transfer and the average surface temperature of the cylinder. This relation appears to indicate that variations in the surface temperature of the cylinder do not materially modify the flow conditions.

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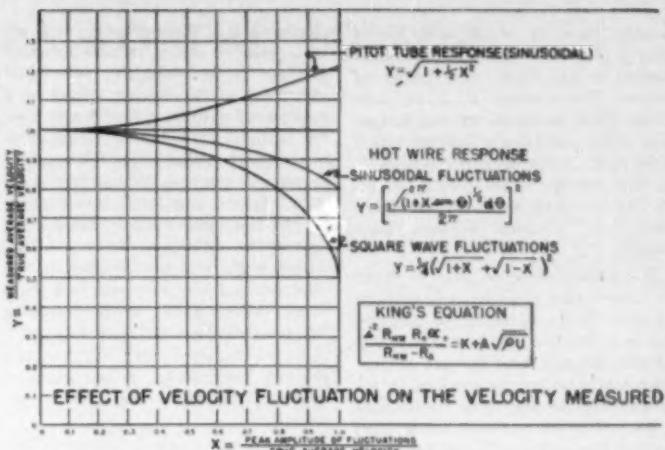


Fig. A.

#### Discussion

**R. S. Levine** (North American Aviation, Inc., Los Angeles, Calif.): Since the stated object of the present investigation is to submit detailed information concerning temperature and air speed profiles in the wake of a heated cylinder, this discussion is based on the interpretation of the instrument readings, a factor that may affect the accuracy of the data presented.

The authors correctly emphasized that the hot wire anemometer, as used here, does not indicate the direction of flow, but merely measures the magnitude of its component in the plane perpendicular to the axis of the wire. Consideration has not been given, however, to the effect fluctuations in this speed have on the measurement of the average velocity at a given point in the flow.

The Reynolds number of the flow in these experiments, based on the diameter of the cylinder, range from about 1000 to 5000. These Reynolds numbers are well within the range of 100 to 100,000 where eddies form and break away from alternate sides of the cylinder, creating the well-known Kármán vortex trail (1). At a given point close behind the cylinder, then, the instantaneous speed may actually vary alternately from a value near zero to a value near the free stream velocity.

The kind of average speed measured by a hot wire anemometer under these conditions is not the same as the true average, defined as that which could be used in a material balance.

The response of a hot wire anemom-

eter may be described by King's equation:

$$\frac{i^2 R_{HW} R_A a_0}{R_{HW} - R_A} = K + A \sqrt{\rho U}$$

where:

$i$  = heating current, amp.

$R_{HW}$  = resistance of wire at operating conditions, ohms

$R_A$  = resistance of wire at air temperature, ohms

$a_0$  = resistance of wire at 0°C.

$a_0$  = temperature coefficient of resistance based on 0°C., ohm/ohm °C.

$\rho$  = density of air, lb./cu.ft.

$U$  = velocity of air, ft./sec.

$K$  and  $A$  = empirical constants depending on the wire

The current needed to maintain the wire at a given resistance then, is a measure of the time average value of the square root of the instantaneous speeds. This current, and hence the speed indicated by the instrument, is not the same as if the actual flow had been steady at the true average speed. The decrease in heat transfer when the instantaneous speed is less than average is larger than the increase in heat transfer at higher than average speeds.

The error involved is shown in Figure A for two types of velocity fluctuations, sinusoidal and square wave. A plot

showing the error which would obtain using a pitot tube with sinusoidal fluctuations is also shown as a matter of interest. The abscissa  $X$ , is the ratio of the peak amplitude of the fluctuations to the true average velocity, and  $Y$  is the ratio of the measured velocity to the true average velocity. If the direction of the flow shifts as the speed varies, the situation becomes more complex.

The similar objection may be raised for temperature measurements with the hot wire. If the instantaneous temperature is a function of the instantaneous velocity, the measured average temperature would be heavily weighed by the temperature existing when the velocity is low. At usual conditions of turbulent channel flow, where  $X$  may be of the order of 0.05, the error with either of these instruments is negligible.

It is apparent the above criticism does not apply at a distance of 1.69 in. downstream from the cylinder. Here, an integration of the velocity traverse given by the authors, corrected for temperature, making it in effect, a mass balance, agrees with the average velocity of 24.8 ft./sec. In regions close behind the cylinder, however, where because of this eddy shedding effect,  $X$  may approach 1.0, and the measured velocity may be on the order of 20% less than the true velocity.

No measurements of the amplitude of the fluctuations are recorded in the present investigation, and, as Mr. Mason said, it is in the region just behind the cylinder where the results do not agree with theory. In view of the possibility that fluctuations are large at some points behind the cylinder, it would be desirable to measure these fluctuations to prove the accuracy of all the data.

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#### Written Discussion

**B. H. Sage:** The existence of velocity fluctuations in turbulent flow is well known, and its particular importance in connection with the vortex trails in certain parts of the wake of a cylinder (1, 2, 5) in a turbulent flowing stream must be considered as pointed out by the author of the discussion. For the purposes of correlating the macroscopic characteristics of the transfer of mo-

mentum and of thermal energy it is advantageous to utilize suitable temporal averages in describing the temperature and speed of the flowing stream as a function of position. With this in view the authors attempted to utilize techniques which yielded reasonable temporal averages throughout the majority of the wake. In the interest of brevity mention of the significance of these averages in the vicinity of the axis of the vortex trails was not included in the basic presentation. However, as a result of the interest shown in the foregoing it appears desirable to review briefly the methods employed and indicate the probable uncertainties in the measurements of temperature and speed in vortex trails.

The discussion which follows is limited only to the conditions believed to exist in the vortex trails. The magnitude and the period of the air speed fluctuation in the vortex trails are both much larger than is found in other parts of the turbulent stream. Therefore in the vortex trails the uncertainties in the temporal averages for the temperature and speed of the flowing fluid are at a maximum (1). It appears that the fluctuations are essentially sinusoidal with a maximum frequency of 90 cycles/sec. (2, 3, 5), and a representative value of the ratio of the maximum amplitude of the fluctuating speed to the mean speed varies from a small value at the edge of the vortex trail to a narrow maximum of 0.44 at the axis of the vortex trail 0.1 in. downstream from the center line of the cylinder (1). From the data presented in the discussion it appears that sinusoidal fluctuations with an amplitude of this order of magnitude cause an uncertainty in the designated average air speed of less than 1% throughout the majority of the vortex trail and to a maximum uncertainty of 2.5% at a distance of 0.1 in. downstream of the center line of the cylinder.

The foregoing is based on the premise that the frequency of the fluctuations encountered in the vortex trails in the wake of the cylinder was sufficiently small that the hot wire anemometer employed would respond to the fluctuations in speed in the two-dimensional stream at a particular instant with negligible lag. The measurements were made with a maximum of 200°F. difference between the average temperature of the wire and the bulk temperature in the wake of the stream. Under these conditions of measurement the analysis (1) of the behavior of small diameter wires in turbulent air streams indicated that the lag in the response of the wire em-

ployed was negligible and therefore no correction from this source need be made. However, if much higher gross velocities had been employed in the working section the frequency of the fluctuations in the vortex trail would have been sufficiently high to make desirable the use of a compensated electronic circuit (4) or other means of correction for the temporal deviation of the average characteristics of the wire from its equilibrium behavior in the rapidly fluctuating stream.

Even though the wire reflects the variation in speed as a function of time, under the conditions of flow being considered there exists a small uncertainty in the average employed. In so far as the fluctuations are concerned the wire may be treated under conditions of constant current. Use of a galvanometer with a significant moment of inertia yields at a frequency of approximately 90 cycles/sec. a linear average of the resistance fluctuations of the wire. The resistance varies nearly as the square root of the velocity, and therefore the difference between the average of the square root of the velocities and the average of the velocities is involved. As indicated in the discussion this results in an error in the temporal average which depends upon the amplitude of the fluctuations, and this error varies from a negligible value in the normal turbulent flow at the edge of the vortices to a sharp maximum of 2.5% immediately downstream of the cylinder at the center of the vortex trail.

The foregoing has applied to the air speed. If the wire follows the temperature fluctuations the linear average represents the true temporal average within the uncertainty of measurement. In addition it is desired to indicate that with increasing distances downstream the influence of fluctuations in the vortex trails becomes much less pronounced as the stream again assumes the characteristics of normal, turbulent flow.

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(Presented at Tenth Regional Meeting, Los Angeles, Calif.)

# LETTERS TO THE EDITOR

## BATCH RECTIFICATION

Sir:

Possible users of the "Batch Rectification" relations proposed by Chu (*Chem. Eng. Progress*, **46**, 215 (1950)), will be greatly aided by a fuller statement of the limitations of such methods. These limitations arise through inapplicability of the McCabe-Thiele procedure in batch fractionation with appreciable holdup and from the limited applicability of the Eshaya procedure.

Eshaya (*Trans. Am. Inst. Chem. Engrs.*, **43**, 55 (1947)) stated in his original paper that his method gave incorrect answers when actual reflux was less than about 1.07 times minimum reflux. This is because such calculations involve approach to pinch point conditions. Trial calculations in this laboratory indicate that the method sometimes fails for reflux ratios as much as 1.5 times the minimum reflux (see Table 1).

It appears that for batch distillation the Eshaya method is of uncertain value when applied to mixtures with relative volatility less than about 1.2 or 1.3. For such values of alpha, and any reasonable separation, the slope of the operating line is so near unity that all reasonable operating reflux ratios will necessarily be within 1.5 times the minimum reflux ratio. Eshaya's example 3 apparently works out satisfactorily because of the extremely high operating reflux ratio,  $R = 1000$ .

An even more general restriction for the Eshaya method in batch distillation probably arises from the approach to a pinch point at the upper end of the McCabe-Thiele diagram during the entire period when the more volatile component is being produced in high purity.

These uncertainties are necessarily carried over into the Chu equations, although in some cases fortuitous cancelling of various errors may occur in such a way as to give approximately correct results. It seems clear that even with negligible holdup, incorrect results are possible in many cases because of

the limitations inherent in the Eshaya procedure.

Colburn and Stearns (*Trans. Am. Inst. Chem. Engrs.*, **37**, 291 (1941)) pointed out in 1941 that in batch distillation with appreciable holdup the change of composition with time produced an entirely different material balance relation than that underlying the McCabe-Thiele procedure and the Smoker equation. The Colburn-Stearns experiments confirmed the existence of completely different composition relations from those predicted by the simple steady-state theory. Forthcoming publications from this laboratory will describe similar results under a variety of conditions.

This work indicates that even as little as 3% holdup (based on initial charge) may give compositions considerably different from what the simple theory predicts. Such effects are much influenced by reflux ratio, occur at reflux ratios commonly used, and are present in multicomponent distillation.

The derivations of Chu are doubly dependent upon the McCabe-Thiele procedure, since it underlies both the relations of Smoker and of Eshaya.

It is not intended to imply that the simple McCabe-Thiele-Smoker relations are always inapplicable in batch distillation with normal operating holdup. However, these simple relations are frequently inapplicable, and since there is at present no means of predicting conformity, all derived results should be used with due caution.

July 10, 1950

Arthur Rose,  
State College, Pa.

Sir:

The batch rectification described in my article (*Chem. Eng. Progress*, **46**, 215 (1950)) refers to one of maintaining constant distillate composition by continuously increasing reflux ratio. The comments made by Dr. Rose undoubtedly refer only to the batch rectification operated under a constant reflux

ratio. It is therefore less likely that the same discussion will hold.

In deriving the composition of holdup on each plate at the cutting point, the same relation of material balance underlying McCabe-Thiele's procedure has been employed by the following reasoning which indicates that the unsteady-state condition in a batch column has never been overlooked.

If a material balance of a volatile component is made at the cutting point around the  $n$ th plate and the overhead product of a batch distilling column over a differential interval of time, the following equation will result:

$$Y_{n+1} dV = X_n dO + X_D dD + n Q dX_n' \quad (1)$$

where

$V$  = moles of vapor flowing upward from plate to plate

$O$  = moles of liquid flowing downward from plate to plate

$dX_n'$  = differential change in the average composition of holdup on the plates between  $n$ th plate and the condenser

Other notation is referred to in *Chem. Eng. Progress*, **46**, 215 (1950).

Since the reflux ratio is defined as  $dD/dO = -dS$ , Equation (1) can be rearranged, giving:

$$Y_{n+1} = \frac{R}{R+1} X_n + \frac{1}{R+1} X_D - \frac{n Q dX_n'}{(R+1) dD} \quad (2)$$

This equation is essentially the same as that derived by Colburn and Stearns (*Trans. Am. Inst. Chem. Engrs.*, **31**, 291 (1944)), and can be used to relate product and still composition as well as to determine plate-by-plate composition at the cutting point during the batch rectification under constant distillate composition.

To solve Equation (2) a knowledge of the variation of the composition of holdup on each plate with overhead take-off, which is unknown before the solution of Equation (2), is necessary. For this reason a straightforward analytical solution is impossible. The trial-error procedure involved in laborious and even less reliable (*Trans. Am. Inst. Chem. Engrs.*, **31**, 291 (1944)).

Fortunately, in the batch rectification under the condition of constant distillate composition, the reflux ratio is increased continuously to maintain a constant composition of the overhead product. At the cutting point where the reflux

TABLE I.—TRIAL ESHAYA CALCULATIONS  
(Rectifying Section Only)

Trial No.	Head Composition	Pot Composition	Reflux Ratio $L/D$	Min. Reflux Ratio	$N$ Eshaya	$N$ McCabe Thiele	$N$ Smoker
2a	6.8	2.1	49.2/1	32.6/1	22.3	27	...
2b	10.85	2.0	96.5/1	71/1	31.4	35	35.4
2c	18.10	2.1	196/1	132/1	40.5	46.7	46.8
4a	12.90	2.1	96/1	76/1	35.0	44.5	...

Compositions are mole %  $n$ -heptane in mixture with methylcyclohexane.

ratio is usually high, the change of hold-up composition with overhead take-off represented by the term  $dX_b'/dD$  in Equation (2) can be very small.

In view of the difficulty mentioned previously,  $dX_b'/dD$  is assumed to be zero, and the last term of Equation (2) drops off to give the following term:

$$Y = \frac{R}{R+1} X_a + \frac{1}{R+1} X_D \quad (3)$$

This equation has been used in my paper only to relate product and still composition and to derive plate-to-plate composition at the cutting point during batch rectification under C.D.C.

Eshaya's method seems to be a faster and simpler method available for the calculation of binary systems in the continuous fraction. In view of its empirical nature and the agreement with 29 systems involving both ideal and non-ideal ones claimed by the author, we have made some study to compare the results calculated by Eshaya's method with those by McCabe-Thiele's and Smoker's.

In an unpublished report, Robert V. Herman of Mallinckrodt Chemical Works, studied binary systems with relative volatility ranging from 1.1 to 6.5 under three operating reflux ratios; namely:  $2 R_{min}$ ,  $3 R_{min}$ , and  $4 R_{min}$ . The feed, a mixture of 50% liquid and 50% vapor, contains 0.4 mole fraction of the low boiler and is separated by continuous fractionation into an overhead of 75 mole %, and a bottom of 5 mole % in the low boiler. The number of theoretical plates necessary to bring about the required separation was calculated first by Eshaya's method under different operating conditions for different systems. For relative volatility from 1.1 to 1.4, Smoker's equation was used for comparison. For relative volatility higher than 1.5, the graphical method of McCabe-Thiele was employed. Since Eshaya's equations are sensitive to slide-rule calculation, calculating machine has been used throughout the calculation. The results of calculation are presented in Table 2.

The following conclusions might be drawn from our study:

TABLE 2.—COMPARISON OF CALCULATED NUMBER OF THEORETICAL PLATES

Relative Volatility	Enriching Eshaya's Reflux Ratio	Number of Theoretical Plates					
		Enriching		Stripping		Total	
		Smoker's or McCabe- Thiele's	Eshaya's	Smoker's or McCabe- Thiele's	Eshaya's	Smoker's or McCabe- Thiele's	Eshaya's
<b>I. Operating Reflux Ratio = <math>2 R_{min}</math></b>							
1.1	20.78	22.0	22.81	26.74	64.53	60.74	+ 6.24
1.2	11.99	11.28	20.78	19.96	20.87	21.04	+ 0.42
1.3	7.50	8.00	16.49	14.08	24.08	22.08	+ 9.04
1.4	5.80	6.28	12.05	10.96	18.94	17.19	+ 10.02
1.5	4.98	5.26	11.15	8.59	16.03	13.85	+ 15.95
1.7	3.68	4.00	8.96	6.77	12.64	10.17	+ 17.35
2.0	2.70	2.98	7.34	5.44	10.13	8.87	+ 16.85
2.5	2.08	2.79	6.16	3.82	8.24	6.81	+ 24.7
3.0	1.71	2.05	5.64	3.52	7.35	5.57	+ 32.0
3.5	1.48	2.00	5.39	2.91	6.88	4.91	+ 40.2
4.0	1.30	2.00	5.28	2.80	6.63	4.49	+ 44.6
4.5	1.20	2.00	5.17	2.19	6.49	4.19	+ 54.8
5.0	1.15	1.96	5.01	2.02	6.44	3.88	+ 60.0
5.5	1.08	1.75	5.4	1.98	6.46	3.73	+ 73.3
6.0	1.00	1.67	5.53	1.93	6.53	3.60	+ 81.4
6.5	0.94	1.59	5.68	1.84	6.63	3.43	+ 93.0
<b>II. Operating Reflux Ratio = <math>3 R_{min}</math></b>							
1.1	18.52	19.31	27.30	33.60	55.92	53.00	+ 5.52
1.2	10.00	10.02	19.51	17.33	39.60	37.37	+ 8.15
1.3	6.98	7.09	13.95	12.16	30.92	19.25	+ 8.73
1.4	5.47	5.48	11.02	9.49	16.49	14.97	+ 10.01
1.5	4.58	5.00	9.30	7.21	13.94	12.21	+ 14.15
1.7	3.51	3.07	7.43	6.30	10.94	9.37	+ 16.75
2.0	2.88	3.00	6.80	4.43	8.71	7.43	+ 17.25
2.5	2.08	2.18	4.80	3.28	6.89	5.11	+ 22.2
3.0	1.75	2.00	4.39	2.89	6.14	4.82	+ 27.4
3.5	1.55	2.00	4.13	2.35	5.66	4.25	+ 33.2
4.0	1.41	1.84	3.95	2.02	5.36	3.86	+ 38.9
4.5	1.30	1.70	3.85	2.04	5.15	3.74	+ 37.8
5.0	1.22	1.56	3.81	1.86	5.03	3.42	+ 47.2
5.5	1.15	1.43	3.79	1.83	4.94	3.25	+ 52.0
6.0	1.09	1.34	3.80	1.79	4.89	3.13	+ 55.6
6.5	1.04	1.34	3.82	1.72	4.86	2.96	+ 64.3
<b>III. Operating Reflux Ratio = <math>4 R_{min}</math></b>							
1.1	17.68	18.21	34.75	31.29	52.36	49.50	+ 5.18
1.2	9.65	9.50	18.18	16.45	27.83	25.95	+ 7.25
1.3	6.71	6.63	13.00	11.45	19.71	18.09	+ 8.96
1.4	5.39	5.19	10.20	8.91	15.49	14.09	+ 9.96
1.5	4.44	4.10	8.63	7.10	13.07	11.60	+ 12.55
1.7	3.44	3.58	6.11	5.39	10.25	8.77	+ 16.85
2.0	2.88	3.00	5.45	3.94	8.13	6.84	+ 18.85
2.5	2.08	2.00	4.41	3.38	6.49	5.33	+ 21.70
3.0	1.77	2.00	3.90	2.45	5.67	4.45	+ 27.50
3.5	1.58	1.92	3.61	2.01	5.19	3.93	+ 32.1
4.0	1.45	1.69	3.44	1.98	4.89	3.67	+ 33.3
4.5	1.35	1.54	3.32	1.92	4.67	3.46	+ 36.2
5.0	1.27	1.40	2.25	1.78	4.52	3.18	+ 42.2
5.5	1.20	1.25	2.21	1.74	4.41	2.99	+ 47.5
6.0	1.15	1.16	2.19	1.70	4.34	2.82	+ 48.7
6.5	1.10	1.06	2.17	1.77	4.27	2.63	+ 50.9

1. At a constant value of operating reflux, the % deviation of Eshaya's method increases with the increase of the relative volatility.

2. At a fixed value of the relative volatility, the % deviation of Eshaya's method increases in the following order:

$$4 R_{min} < 3 R_{min} < 2 R_{min}$$

The higher the operating reflux ratio, the lower is the deviation of Eshaya's method. There is little difference in the deviation between the case of  $4 R_{min}$  and that of  $3 R_{min}$  for these systems with the relative volatility below 5. However, the difference of deviation between the cases of  $3 R_{min}$  and  $2 R_{min}$  is quite significant, and increases with the value of the relative volatility. At the relative volatility of 6.5, the % deviation of Eshaya's method at  $3 R_{min}$  and  $2 R_{min}$  are 64.3 and 93 respectively, while the corresponding deviations at the relative volatility of 4 are 38.9 and 46.8. For the systems with the relative volatility below 2.5, Eshaya's method at all these three operating reflux ratios gives substantially the same extent of deviation.

3. Being aware of the fact that the present study is made to the cases of constant condition regarding composition of the feed and the fixed composition for both bottom and overhead products, I am in no position to extend the same conclusion to the cases where the other conditions of the feed and the composition of pot, overhead and feed are involved. However, similar calculations for the cases where

$$X_f = 0.6, q = 1$$

$$X_b = 0.95$$

$$X_w = 0.05$$

at  $1.5 R_{min}$  and  $3.5 R_{min}$  indicate that the percentage deviations of Eshaya's method are usually much smaller. The relative volatility used in the calculation ranges from 1.2 to 2.0.

Although the limitations of the derived methods are clear from the derivation itself, it might be advisable to recapitulate them here:

1. Universal assumptions leading to McCabe-Thiele's procedure. In case the system contains components of unequal molal heat of vaporization, the same equations can be used provided the fictitious molecular weight is introduced.

2. Mathematical approximation of the summation of finite number of terms into an integral. This implies that the results calculated from the derived equations are closer to the true values, the larger the number of theoretical plates in the distilling column.

3. Those expressions containing the term of relative volatility, "a," will yield the correct results if "a" of the system changes little with the composition of the liquid.

4. The equations derived through the introduction of Eshaya's equations are necessarily governed by the same limitation of the latter.

5. The item  $\frac{dX_b'}{dD}$  is negligible at the cutting point under the conditions of constant distillate composition.

August 7, 1950

Ju Chin Chu,  
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# THE MOST PERSISTENT PUMPING PROBLEMS FOR CHEMICAL PLANT DESIGNERS

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WHETHER the pumps required for a particular plant represent a minor item or a matter of some concern to the chemical engineers, two pump problems generally arise before design has gone very far. These problems are recurrent, and the more persistent in that there seem to be no clean-cut guides to the right answers. One of these is selection—selection of the main type at least—and this problem is interrelated with the other, as will be seen.

*Selection Simplified.* It is felt that selection is only a problem for the "unusual circumstance," and that for well-known services usually encountered, the proper pump types are quite well established. This being true for the most part, just what is the unusual circumstance? Since examples would be too multifarious for this discussion it might best be defined as any set of pump service conditions that make pump selection a problem, instead of an easy step in plant design.

It should simplify the problem if the first step of pump selection is approached "in reverse." In other words, instead of considering each of the many factors affecting the best choice of a pump type, and citing some of the general rules to which exceptions are legion, it can be said, "Always use a centrifugal-type pump." And then, of course, the statement must be qualified, "Nearly always." For this approach, see Figure 1.

This list of five situations in which centrifugal pumps are not well suited may seem to cover a great many exceptions to this single compendious rule. But when all the pump applications in

many different chemical plants and refineries are considered, these five exceptions are really few. Probably 90 per cent of the pumps will still be found centrifugal-type, if too many of the older plants are not included.

The main reasons that militate against reciprocating pumps are their pulsations, fluctuations, and everlasting valve actions, their wearing parts, their extreme size for high capacities, and their need of relief valves. Rotary pumps also require relief valves although they do not have the other drawbacks of reciprocating pumps. Yet rotaries are frequently ruled out on selection because of their

usual utter dependence on a lubricating quality in the liquid being pumped, and dependence on close clearances between precision-made parts that should not rub. Reciprocating and rotary pumps both have a further disadvantage, when motor-driven, of requiring either wasteful by-passing or extra equipment to obtain capacity variation.

It might be stated that "unusual circumstances" are those that require anything other than a centrifugal pump, for example: the rotary pump for good lubricants at high pressure or at high viscosity; reciprocating pump for non-lubricants at high pressure and high

IN GENERAL, FOR INDUSTRIAL PUMP APPLICATIONS (OUTSIDE OF LABORATORIES),

## SELECT CENTRIFUGAL TYPE PUMPS UNLESS:--

- (a) THE VISCOSITY IS TO BE GREATER THAN 5000 SSU (1000 CP.) AT PUMPING TEMPERATURE.
- (b) THE PERCENTAGE OF UNDISSOLVED GAS BY VOLUME IS TO BE GREATER THAN 8%, OR IF SMALLER PERCENTAGES ARE NOT WELL DISPERSED.
- (c) THE PERCENTAGE OF SOLIDS BY VOLUME IS TO BE GREATER THAN 50%, OR IF SMALLER PERCENTAGES ARE NOT WELL DISPERSED.
- (d) THE ANTICIPATED CAPACITY & DIFFERENTIAL-PRESSURE CONDITIONS FALL TO THE LEFT OF THE SHADeD AREA IN GRAPH.
- (e) THE LIQUID IS TO BE A GOOD CLEAN LUBRICATING OIL BELOW 150°F., FOR A CONSTANT CAPACITY LESS THAN 100 GPM.

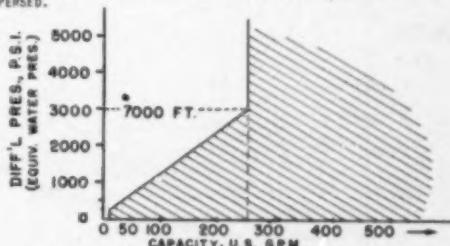


Fig. 1.

TYPE OF PUMP	EFFECT ON PUMP CAPACITY, DUE TO GAS ENTRAINMENT		TYPE OF PUMP	COMMENTS ON THE EFFECT OF GAS ENTRAINMENT	
	DUE TO MARGINAL-NPSH	EFFECT OF MARGINAL-NPSH		EFFECT OF GAS ENTRAINMENT	EFFECT OF MARGINAL-NPSH
RECIPROCATING	MILD REDUCTION	SEVERE REDUCTION	RECIPROCATING	GOOD SELF-PRIMERS.	HEAD-LOSS REQUIRED TO LIFT VALVES DUE TO GAS FLUSHING, VAPOR-EL- IMINATE, AND COMPRESSED AIR EXPANSION. HEAD-LOSS IS QUITE HIGH IN ALL BUT A FEW TYPES.
ROTARY	MILD TO MODERATE REDUCTION	SEVERE REDUCTION	ROTARY	FAIL TO GOOD SELF-PRIMERS, DE- PENDING OF DRAWSHEETS.	
PERIPHERAL	MILD TO MODERATE REDUCTION	SEVERE REDUCTION	PERIPHERAL (ALSO CALLED TURBINE-TYPE, REGENERATIVE, SIDE-CHANNEL, OR SIDE-CHANNEL-1)	FAIL TO GOOD SELF-PRIMERS.	POSITION OF LIQUID CHANNEL THROUGH THE "TURBINE" FROM EJECTOR TO DISCHARGE MAY FLAIL, AND VAPOR VOLUME RESTRICTS INLET OF MORE LIQUID.
CENTRIFUGAL	SEVERE TO TOTAL REDUCTION	MILD TO MODERATE REDUCTION	CENTRIFUGAL	FAIL NOT SELF-PRIMING, IF DISCHARGE IS CLOSED, MAY REQUIRE FREQUENT SHOPS AND STARTS FOR VENTING WHILE STOPPED, OR AUXILIARY RE- PRIMING DEVICES TO REMOVE ACCUM- ULATED GAS.	CENTRIFUGAL, THOSE WITH LOWER HEAD- LOSSES THAN MOST ALL OTHER TYPES, AND VAPORIZATION IS "LOCAL" (DUE TO PORTIONS OF WHEEL-PASSAGES WHICH DO NOT SLIDE OFF HIGH FLOW).

Fig. 2.

Fig. 3.

viscosity, for high percentages of undissolved gases. However, to go more deeply into such selections, the particulars of each one should be made known. One could write about a few unusual cases where as a last resort a clamshell bucket was required, or at the other extreme, a conveyor carrying closed containers of liquefied-gas, to "pump" as desired. Before a pump-selection problem gets to be this bad, it is wise to hold a conference of members from several different departments involved, as it may be necessary to alter the process or to design a brand new type of pump.

However, there are enough unusual circumstances in the great broad field where centrifugal pumps are used to focus attention on these. The circumstances may be unusual in the sense that some of the service conditions make it unwise to select a conventional size, type and arrangement of centrifugal pump. Chemical engineers hardly ever

have to select the particular sizes and the subtypes of centrifugal pumps themselves, but they can hardly avoid getting mixed up in the selection. (Boiling and near-boiling liquids in tanks at low elevations have seen to that.) Chemical engineers not only set the conditions of service but also are often the ones who decide tank locations, tower heights, line sizes, whether exchangers are to be in the suction or the discharge lines, and most important of all, what the vapor-pressures will be. So they find themselves helping with the suction problem, also known as the net-positive-suction-head (NPSH) problem.

The possible release of gas or vapor from a liquid being pumped is a primary problem to consider in plant design. It is a more fundamental consideration than the possible presence of any solids in the liquid because, whereas either vapors or solids may restrict a pump's capacity and increase maintenance costs, gas-bindings or vapor-locks often throttle

the plant or prevent pumping altogether. *Thus plant design is limited by pump-suction requirements, and pump selection is affected by plant design.* Here, one is brought face to face with that other most persistent pump problem.

*Can the NPSH Problem Be Simplified?* Writers on this subject and others who have been stressing this point in the last few years have seemed to make the problem more confusing. But it previously seemed simple largely because it was being ignored. Perhaps a reminder or two on NPSH terminology is appropriate at this point. First, NPSH and static-suction-head are seldom synonymous. The word *net* is the important one. It is the excess of pressure at the pump-suction nozzle, over and above the vapor pressure, that gives the best criterion so far discovered of a pump's permissible capacity.\*

It is important also to distinguish the effect of insufficient NPSH from the effect of gas entrainment, on various types of pumps. This throws the subject back to selection. (See Figs. 2, 3.) It will be noted that gas entrainment (say 10% by volume) has rather little effect on pump capacity for the first three main types—reciprocating, rotary, and peripheral. (These peripheral pumps are also called turbine-type, regenerative, side-channel, or turbulence type.) But gas entrainment causes severe-to-total reduction of pump capacity for centrifugal-type pumps; this may be their most serious weakness. Conversely, if the NPSH is marginal, the reciprocating, rotary, and peripheral pumps are likely to suffer severe reduction in capacity, whereas the centrifugal pumps are only moderately affected. (Marginal NPSH might be about 4 ft. at 100 gal./

\* The vaporization that makes for all this suction trouble is a physical phenomenon that has yet to be fully understood. Possibly more will be learned when scientists unlock more secrets of the fracture of liquids, of negative-pressures, of liquids in "tension," that are known to exist in nature.

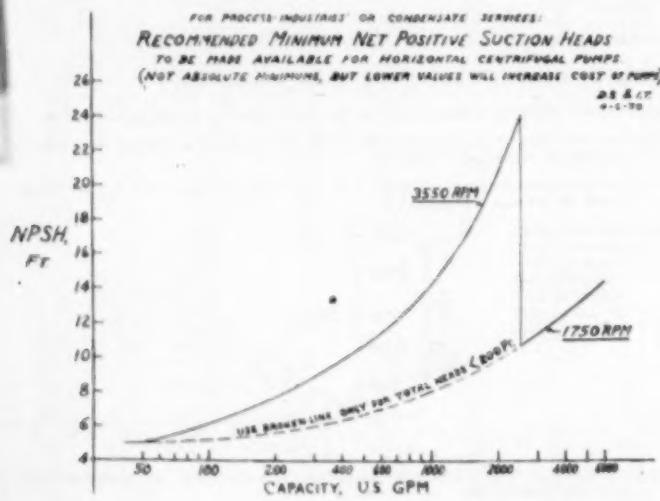


Fig. 4.

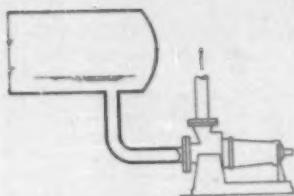


Fig. 5. Base case. If liquid is boiling or near-boiling, static head may be insufficient for operation at required capacity. Various solutions follow.

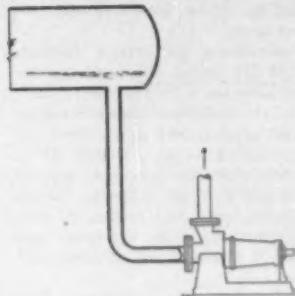


Fig. 6. Solution No. 1. Elevate the supply vessel.

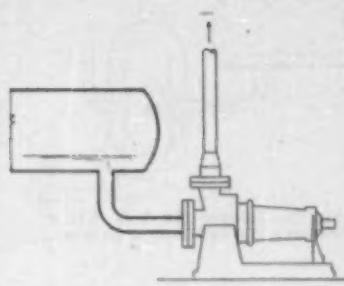


Fig. 7. Solution No. 2, A. Use a larger pump.

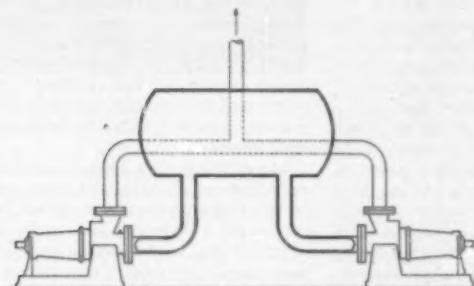


Fig. 8. Solution No. 2, B. Use multiple pumps in parallel.

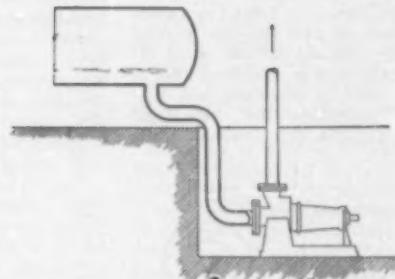


Fig. 9. Solution No. 3, A. Lower the pump in a pit.

min., for instance.) These tabulations may not be sufficiently quantitative, but they serve to emphasize the difference in effect on pump capacity due to gas entrainment, compared with marginal NPSH. It also explains why there have been so many efforts to make a real self-priming centrifugal pump, to improve the type that is otherwise so nearly ideal.

Confining this discussion to NPSH again it is noted that Figure 4 shows a curve of recommended minimum net-positive-suction-heads plotted against

capacity, for horizontal centrifugal pumps of representative U. S. manufacturers. Values of required NPSH that are shown by this curve are not nearly so conservative as similar values recommended by the Hydraulic Institute, but this curve is drawn for process industries and condensate-pump services, where a little cavitation can be tolerated. The Hydraulic Institute's recommended minimums apply for boiler-feed pumps largely, where cavitation is a more serious problem. Neither set of curves

shows absolute minimums, but lower values of available NPSH will usually increase the cost of pumps. However, when designing a chemical plant interest is not centered so much in preventing the destructive effects of cavitation (such as the pitting of impeller vanes) as in the assurance that the pumps do not "bottleneck" the plant.

NPSH difficulties are not only frequent today, but also are becoming worse; at least they will be much more prevalent. Perhaps it can be stated that

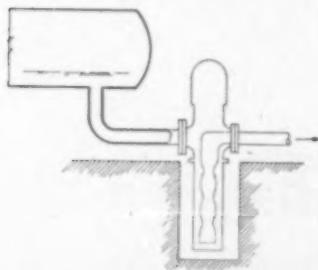


Fig. 10. Solution No. 3, B. Use a vertical pump in a "barrel" or cylindrical can, with first-stage impeller as low as necessary.

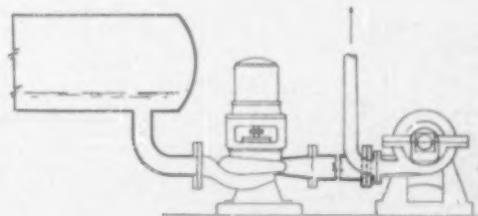


Fig. 11. Solution No. 4, A. Use a booster pump (low-head centrifugal-type).

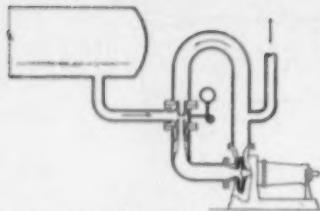


Fig. 12. Solution No. 4, B. Use a booster pump (one form of jet type).

understandings of the suction problem and the effects of low NPSH are being clarified more and more, even if not simplified.

**Solutions and Cures.** Although a curve like Figure 4 is helpful as a guide to the chemical plant designer, ways of providing sufficient NPSH, or of requiring less must be considered also, as well as ways of preventing any gas-binding conditions, for centrifugal pumps. Remedies that previous writers

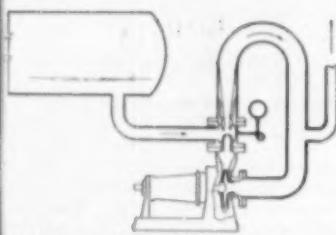


Fig. 13. Solution No. 4, C. Use a booster pump (another form of jet type).

suggested include: (a) reducing entry losses in the pump, (b) increasing suction pressure available at the pump by reducing suction line losses, increasing the liquid supply head, pressurizing the supply tank, or by using a centrifugal booster for positive-displacement pumps, and (c) removal in the suction vessel of entrained and dissolved air. It is here

intended to review these and add two or three more.

In considering the several sketches (Figs. 5-21) which illustrate various ways to solve the NPSH problem (starting with the traditional ones and ending with the lesser-known ones), there are two assumptions to bear in mind. First, all sketches are schematic only and do not adequately show supports, valves, instruments, etc. And second, in each arrangement the inlet line-losses are assumed to be eliminated or made negligible.

Figure 5 shows the "base-case." Forgetting the shape of the vessel, which could just as well be a vertical tower or a spherical tank, one notes that if the liquid is boiling, near-boiling or gassy, this ideal arrangement may not provide sufficient static head and NPSH for operation at the required capacity. The sketch in Figure 6 shows the method most frequently used in the past to solve the problem; an expensive solution if the tower also has many pipes and a steel staircase tied to it, all of which become elongated, not to mention the taller and stronger supports required.

Figures 7 and 8 show the use of a larger pump (with lower required NPSH), or of pumps in parallel. The former is not always possible and the latter is not too satisfactory a way out. In Figures 9 and 10 another well-known method is illustrated—increasing the supply head by lowering the pump instead of raising the supply vessel. Vertical pumps are now being applied widely to solve the NPSH problem.

When high-pressure pumps of any type take suction from low tanks or towers, a separate low-head booster-pump is often used, particularly when the distance from tank to main pump is great. This is illustrated in Figure 11 (solution No. 4, A), but is not to be construed as the only use of a centrifugal booster.

Jets are used also as boosters, usually in combined arrangements with centrifugal pumps. (See Figs. 12 and 13 for two arrangements of such a combination

for hot condensate pumping). Other styles are available in small sizes. Any cavitation that occurs is likely to be in the jet rather than in the pump impeller, probably making for cheaper replacements.

Another solution is subcooling the liquid between tank and pump (Figs. 14 and 15), provided that a colder medium is available. If cooling water is not cold enough, low-temperature refrigeration systems that are used in many light-hydrocarbon plants may be available, so this method can receive more frequent consideration. Combinations of subcooling and boosting are also effective. (See cooling fins; Fig. 16.)

Pressurizing the supply tank, as done with stored high-pressure nitrogen acting on liquid-fuel in turborockets, can hardly be practical in continuous process plants (unless for emergency pump-out perhaps), but pressurizing can be done intermittently by provision of an intermediate vessel or "lock-chamber." An example of this is shown in Figure 17—a scheme used to feed boilers from very small pumps.

The next approach depends on a special construction inside the pump. By constricting the volute at one point, and positioning a stationary port inside the impeller's eye or inlet-opening at a position opposite the volute's constriction, a localized backflow can be produced in the impeller passages as they pass this point. (See Figs. 18 and 19.) If any air or entrained gas is present in the pumpage, it can readily be kept from accumulating in the impeller by connecting a line from the stationary port back to the supply vessel. This is an effective way to prevent gas-binding, and might possibly afford a solution for marginal NPSH. A pump of this design, called a "foam-liquid" pump, has already proved itself for certain paper-mill applications where air-entrainment is at a maximum, and where discharge pressures are not high. To make it suitable for near-boiling liquids, however, such a pump would probably have to be oversized (to keep the inlet losses down)

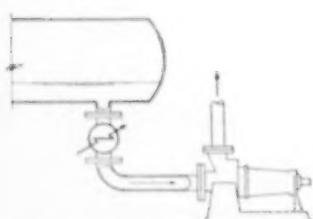


Fig. 14. Solution No. 5, A. Subcool the liquid.

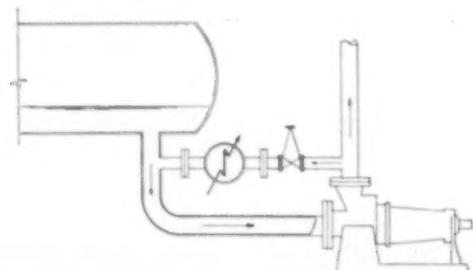


Fig. 15. Solution No. 5, B. Subcool the liquid.

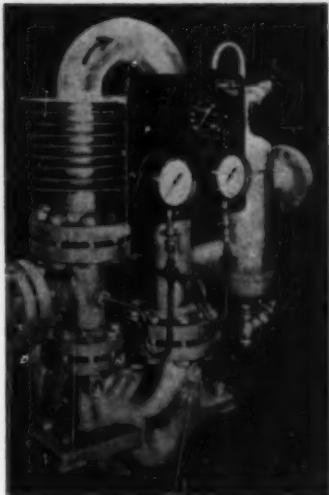


Fig. 16.

and since it might operate with low efficiency, should probably be utilized only as a booster—quite a gamble, even at that.

By now it might reasonably be asked if the NPSH problem cannot be solved by continuous physical removal of vapor-bubbles after they are formed, by evacuation, instead of spending so much

engineering effort on preventing their formation? Four years ago this question was answered by the statement that it might conceivably be done on non-homogeneous liquid mixtures like naphthas and gasolines (that have a boiling range rather than a boiling point) but that it would not, and had not, worked for boiling water. It was said that so great a volume of vapor is evolved when pump entrance-losses reduce a homogeneous liquid to its vapor pressure, that the auxiliary vacuum pump or compressor removing the vapor would be absurdly large. In fact it was thought that all of such a near-boiling liquid would flash.

Yet others were finding at that time, in that very manner, perhaps the most promising solution yet to the NPSH problem, even for homogeneous liquids. Hence this method can be considered further.

Referring to Figures 20 and 21, it should be pointed out that the vapor line that runs from the separate outlet on the special centrifugal pump can be led either to a separate auxiliary evacuating pump or to a "common" one. Since this line will carry also much liquid as well as vapor and gas, the auxiliary evacuating pump must be able to tolerate much liquid—obviously a predisposing

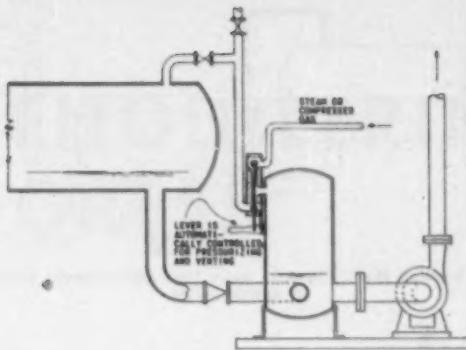


Fig. 17. Solution No. 6. Pressurize intermittently, using a lock-chamber.

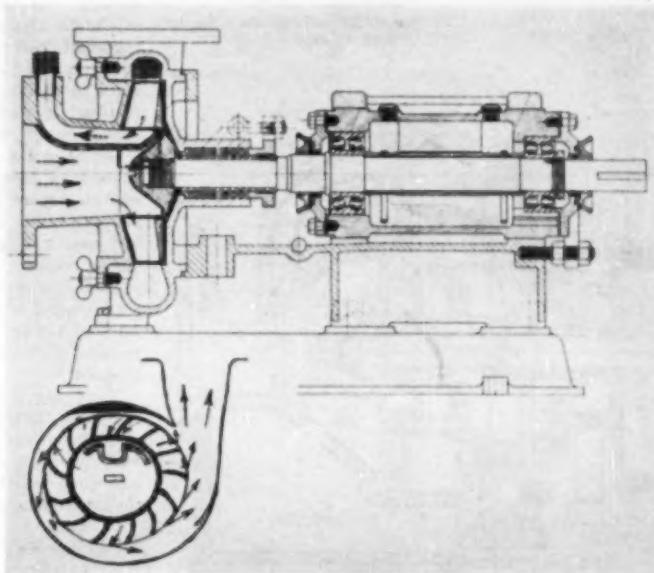


Fig. 18. "Foam-liquid" pump.

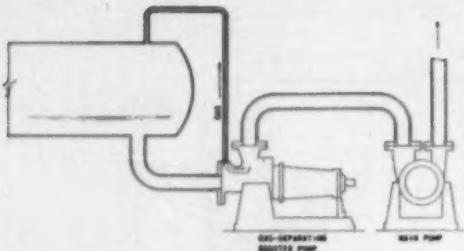


Fig. 19. Solution No. 7. Remove gases (and some vapors), continuously, by special valve.

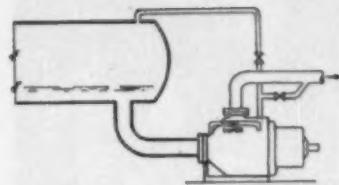


Fig. 20. Solution No. 8. Use special centrifugal pump combined with an auxiliary evacuating pump.

factor toward the liquid-ring type of compressor, also well known as liquid-piston-type rotary compressors and vacuum pumps.

This is not just another combination of a centrifugal pump and a rotary gas compressor similar to earlier self-priming combinations; this pump's construction of impeller and suction-head makes it able to pump continuously with NPSH less than one foot. It is doubtful if any other pumps being made in this country today can do as well in this respect. These pumps should certainly come into wide use as boosters before long. They should also fill the bill as regular process pumps themselves, for the low-pressure, low-capacity services where a somewhat lower efficiency will not be objectionable.

One last solution should be mentioned, i.e., the deliberate evaporation of all the liquid to be pumped, the compression of all of this vapor, followed by condensing at the higher pressure. Such a scheme,

which comprises some of the same equipment as a refrigeration system, would seldom be an economical solution, but it should not be forgotten as a possibility.

### Summary

The solutions to the ever-more-prevalent NPSH problem are as follows:

1. Elevate the supply vessel if cost is slight.
2. A. Use a larger slower pump, with lower inlet losses.  
B. Use pumps in parallel.
3. A. Lower the pump into a pit.  
B. Use a vertical pump with lowered first-stage impeller.
4. A. Use a booster pump, low-head centrifugal type.  
B & C. Use a jet booster. (Can be combined with 5, B.)
5. A. Subcool the liquid, taking all the liquid through a cooler.  
B. Subcool by recirculating a portion through a cooler.

6. Pressurize an intermediate chamber, intermittently.

7. Remove gases, and some vapors, continuously by localized backflow in impeller.

8. Separate vapors from liquid continuously in the impeller of a special centrifugal pump, evacuate and deliver these vapors either to supply vessel or to discharge line as best suited for the process.

9. Evaporate all the liquid, compress, and condense.

### Conclusions

In drawing a general conclusion it can be stated that the selection of the main types of pumps can be simplified considerably and that the NPSH problem and final selection are so tied up with chemical plant design that chemical engineers will have to contribute to the solution of both problems.

Specifically it can be stated that towers and tanks less frequently need to be elevated for industrial pump applications. Although this solution is probably the easiest one for the designer to make, it is not often the cheapest. The several alternatives covered herein would need individual quantitative studies, of course, particularly for those plants involving high-capacity pumps handling near-boiling liquids.

There are wide possibilities for the use of special booster pumps, and great potential savings in the cost of petrochemical plants if these possibilities are explored.

There are many opportunities for pump users to pioneer in both chemical plant design and pump application, instead of waiting for manufacturers who miss many opportunities when they cannot get cooperation of the users on trial installations.

To select the best pump for the unusual circumstance, collaboration is essential.

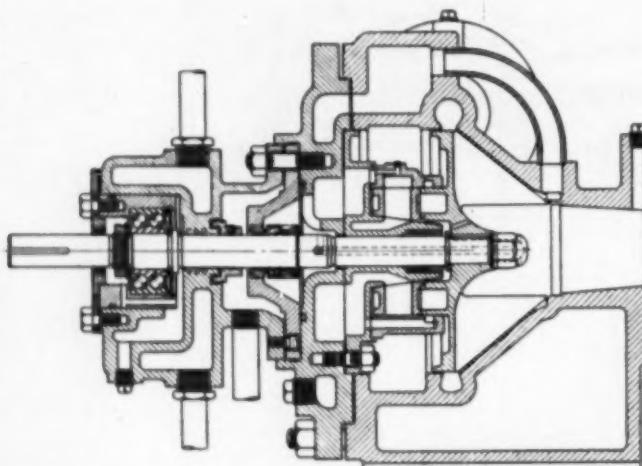


Fig. 21. "Centrivac" pump.

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# NEWLY ELECTED INSTITUTE OFFICERS



**T. H. CHILTON**  
Elected President



**W. I. BURT**  
Elected Vice-President

◀ **T. H. Chilton**, elected President A.I.Ch.E. for 1951, is technical director, development engineering division, engineering department, Du Pont Co. He has been associated with Du Pont since 1925. Since 1935 he has directed the engineering research and development work of the engineering department. Prior to 1925 Dr. Chilton was engaged in research with F. J. Carman, New York. **W. I. Burt** is vice-president, manufacturing, the B. F. Goodrich Co., Cleveland, Ohio. He has been associated with many companies, including Carnegie Steel Co., the Dolomite Products Co., and the Republic Steel Co.



**C. R. NELSON**  
Elected Director



**E. P. STEVENSON**  
Elected Director



**R. C. GUNNESS**  
Elected Director



**R. PAUL KITE**  
Elected Director

◀ **R. C. Gunness** is manager of research, Standard Oil Co. (Ind.). Associated with the Standard Oil since 1938. He has been a group leader, and a section leader in the research department prior to his becoming assistant director, associate director, and manager of research. **R. Paul Kite** is manager, development department, The Dorr Co. He has also been associated with the Krebs Pigment & Chemical Co., and the Mathieson Alkali Works.

## A. I. Ch. E. AWARD WINNERS—1950

THE teaching profession made a clean sweep of the three major awards given annually by the A.I.Ch.E. The Awards Committee and Council released the information in time for Chemical Engineering Progress to make the December issue. The presentations were

### E. R. GILLILAND



"... for contributions in thermodynamics and distillation."

made at the Awards banquet Dec. 5 at the Neil House, Columbus, Ohio.

Dr. Edwin R. Gilliland, professor of chemical engineering at Massachusetts Institute of Technology, was chosen the recipient of the Professional Progress Award. The citation for his work prepared by the Awards Committee stated that it was given to him "for his many contributions to both theory and practice in the fields of thermodynamics, distillation, and gas separation; especially for his work on the reactions of gases under pressure, which led to the principal process for the separation of butadiene in the manufacture of synthetic rubber."

The award, which carries with it a \$1,000 prize, is sponsored by the Celanese Corporation of America, but administered by the A.I.Ch.E. Its purpose is to give recognition to young men in the chemical engineering profession, and one of its provisions is that it go to a man not yet 45 years of age. Professor Gilliland's acceptance address, which was delivered at the banquet, will be published in an early issue of Chemical Engineering Progress.

Professor Gilliland is a native of Oklahoma, received his B.S. degree in chemical engineering (1930) from the

University of Illinois, his M.S. degree (1931) from Pennsylvania State College, and his Sc.D. (1933) from M.I.T. He has an Honorary Doctor's degree in engineering from Northeastern University. His career at M.I.T. began as an instructor in 1934, and he became in succession, assistant professor, associate professor, full professor, and deputy dean of engineering. Dr. Gilliland was also assistant rubber director in charge of research and development in the Office of the Rubber Director during World War II, and has served with the National Defense Research Committee, Joint Chief of Staff—Guided Missile Committee, National Advisory Committee for Aviation, and was Chairman of the Jet Propulsion Panel of the Office

### B. F. DODGE



"... for excellent publication record through the years."

of Field Service, O.S.R.D. He was at one time associate editor of Chemical Reviews, and was joint author of the third edition of "Principles of Chemical Engineering," and the second edition of "Elements of Fractional Distillation." He has previously received the Baekeland Medal and Award for Achievement in Chemistry.

The two previous winners of the Professional Progress Award were Mott Souders, Jr., of the Shell Development Co. in 1949, and in 1948 Allan P. Colburn, provost of the University of Delaware.

### William H. Walker Award

The William H. Walker Award, which is given annually to a member of

the Institute who has made an outstanding contribution to the literature of chemical engineering, went this year to Barnett F. Dodge, professor of chemical engineering and head of the department of chemical engineering at Yale University. The citation read "in recognition of his excellent publication record over the years, and for his recent contributions to Chemical Engineering Progress: 'The Design of Ribbon-Packed Exchangers for Low Temperature Air Separation Plants,' vol. 43, 1947; 'Oxygen Manufacture: Thermodynamic Analyses of Processes Depending on Low Temperature Distillation of Air,' Part 1, and Part 2, vol. 45, 1949."

The purpose of the Walker Award is to stimulate interest in shaping a better chemical engineering literature, and is named after the late Professor Walker of the Massachusetts Institute of Technology.

Professor Dodge, a native of Ohio, received his B.S. degree in chemical engineering from M.I.T. (1917); did graduate work at Harvard University, and received his D.Sc. (1925). Prior

### F. M. TILLER



"... for paper on efficiencies in Gas Absorption, Extraction and Washing."

to his graduate work, he was with the Du Pont Co. for three years, and with the Lewis Recovery Corp. for two. He went to Yale University in 1925 as an assistant professor of chemical engineering, rising to associate professor in 1930, chairman of the department in 1931, full professor in 1935. He has

(Continued on page 18)

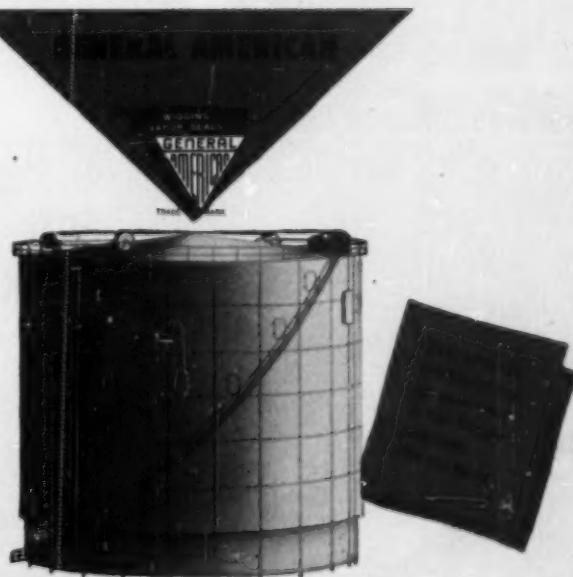


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## CHEMSTRAND TO MAKE NYLON YARN

Osborne Benzanson, president of The Chemstrand Corp., said last month that his company is negotiating a licensing agreement with the Du Pont Co. for the manufacture and sale of nylon yarn. The Chemstrand Corp. would be the first company in America, other than the Du Pont Co., to produce nylon. Du Pont officials also confirmed the negotiations, stating that "Due regard for its other interests and commitments in a diversified chemical business has led Du Pont to the conclusion that it is necessary to broaden and accelerate the effort to meet the unsatisfied demand for nylon fiber. Increasing acceptance of nylon has outpaced Du Pont's plant capacity despite an extensive expansion program, launched before the end of the war, that has tripled production."

Nylon is manufactured in several foreign countries, but negotiations with Chemstrand are the first involving a domestic company."

The Chemstrand Corp. is owned jointly by American Viscose Corp. and Monsanto Chemical Co. It was formed more than over a year ago for research and development work in the field of synthetic fibers and in October announced plans for the construction of a plant at Decatur, Ala., for the production of a new synthetic acrylic fiber.

According to Du Pont, the offer to Chemstrand covers the entire nylon yarn process, beginning with the manufacture of intermediates, hexamethylene diamine and adipic acid, and ending with the production of the finished nylon fiber. Chemstrand's entry into the nylon field, on the scale contemplated, would require a substantial initial capital investment.

Nylon came into being as the result of a program of fundamental research entered into by Du Pont in the late Twenties. Du Pont invested more than ten years of research and development effort and \$27,000,000 before commercial production of nylon was begun in

1939. At that time the intermediates were produced in the Belle Works at Charleston, W. Va., and the fiber at Seaford, Del.

This was followed, at about the time of the entrance of the United States into World War II, by the building of another fiber plant at Martinsville, Va. With the supply of silk from the Orient cut off, nylon immediately became indispensable to the war effort, and production was increased to the maximum possible under the circumstances.

After the war, a third yarn plant was constructed at Chattanooga, Tenn., and its capacity is now being doubled. Capacity at both Seaford and Martinsville has been stepped up greatly since the war.

New plants for the production of intermediates have also been built since the war at Orange, Tex., and Niagara Falls, N. Y. In addition, another intermediates plant is under construction at Victoria, Tex.

(News continued on page 21)

**S. C. Johnson & Son, Inc.**, recently dedicated a new research and development tower shown in this group of pictures, in which the company will carry on its research, development, and control operations. The building was designed by Frank Lloyd Wright and incorporates many features novel to research buildings.

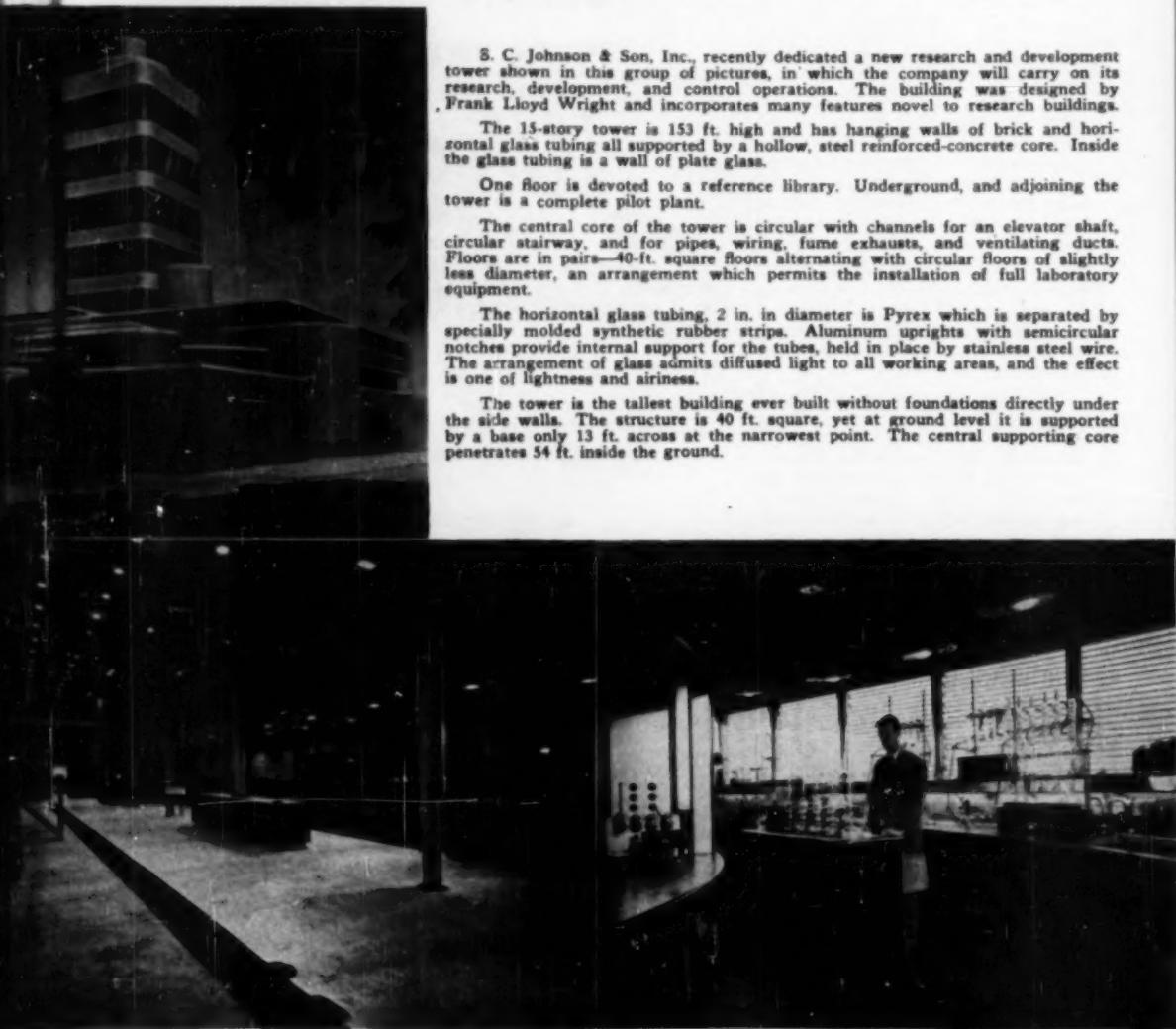
The 15-story tower is 153 ft. high and has hanging walls of brick and horizontal glass tubing all supported by a hollow, steel reinforced-concrete core. Inside the glass tubing is a wall of plate glass.

One floor is devoted to a reference library. Underground, and adjoining the tower is a complete pilot plant.

The central core of the tower is circular with channels for an elevator shaft, circular stairway, and for pipes, wiring, fume exhausts, and ventilating ducts. Floors are in pairs—40-ft. square floors alternating with circular floors of slightly less diameter, an arrangement which permits the installation of full laboratory equipment.

The horizontal glass tubing, 2 in. in diameter is Pyrex which is separated by specially molded synthetic rubber strips. Aluminum uprights with semicircular notches provide internal support for the tubes, held in place by stainless steel wire. The arrangement of glass admits diffused light to all working areas, and the effect is one of lightness and airiness.

The tower is the tallest building ever built without foundations directly under the side walls. The structure is 40 ft. square, yet at ground level it is supported by a base only 13 ft. across at the narrowest point. The central supporting core penetrates 54 ft. inside the ground.



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## AWARDS

(Continued from page 14)

had various consulting positions in research work with the Mellon Institute, Oxygen Process Corp., Connecticut State Water Commission, T.V.A., etc. In November of 1944, he took a year's leave of absence to become technical director of the Fercleve Corp., Oak Ridge, Tenn., where he directed all experimental investigations and plant control work for the company at the Clinton Engineer Works engaged in the separation of uranium isotopes.

For the A.I.Ch.E. he has been a representative on E.C.P.D., Secretary and Chairman of the Committee on Chemical Engineering Education, Chairman of the Chemical Engineering Education Projects Committee, member of the Ethics Committee, and Director of the Institute twice, in 1939-41 and 1943-45. He is the author of numerous technical articles and a book on thermodynamics.

### Junior Award

The Junior Award for 1950 went to Frank M. Tiller, associate professor of chemical engineering at Vanderbilt University. The Awards Committee indicated that it chose Professor Tiller on the basis of his paper, "Efficiencies in Gas Absorption, Extraction, and Washing," published in 1949 in Chemical Engineering Progress.

Professor Tiller is a native of Kentucky, receiving his education at the University of Louisville, where he received a Bachelor of chemical engineering, and the University of Cincinnati which awarded him a Ph.D. degree. He has been chemist with the Colgate-Palmolive-Peet Co., a civil engineer with the U. S. Engineers, instructor at

the University of Cincinnati, and became an assistant professor of chemical engineering in 1942 at Vanderbilt University, an associate professor in 1946. He is also the executive director of the Gupton-Jones College of Mortuary Science. He has authored nine technical papers, three of them in the publications of the Institute.

### Student Contest Winners

The winner of the A. McLaren White Award for first prize was Robert P. Bannon, a chemical engineering graduate of the University of Illinois, June 1950. The A. McLaren White Award is granted to the student who turns in the best solution to a problem selected by the Committee on Student Chapters.

The problem for this year's contest concerned the decolorization of talcum by propane extraction and was selected as one which might confront a young engineer working for a medium-sized company. It required the contestant to devise a flow sheet and design and estimate a process which not only would perform but which would be economically sound. The special subcommittee of the Committee on Student Chapters which prepared the problem was headed by Walter E. Lobo, and included Marvin F. Nathan and Luther Garrett, all of The M. W. Kellogg Co.

Mr. Bannon is at present working on a Shell Fellowship in graduate study in chemical engineering at the University of Michigan. A native of Joliet, Ill., Bannon spent eleven months in the U. S. Navy, re-entering college September, 1946. On graduating from Illinois he achieved one of its highest scholastic honors—that of The Bronze Tablet. He was elected to Tau Beta Pi, Sigma Tau, Phi Lambda Upsilon and Phi Kappa Phi, and he joined Alpha Chi Sigma

professional fraternity. He was also a member of the A.I.Ch.E. Student Chapter.

Second prize went to Leonard R. Brooks, a graduate from the University of Oklahoma. A native of Tulsa, Brooks graduated from Tulsa Central High School in 1933, and after holding various positions, was inducted into the Army in 1942. After discharge in 1946, with a rank of Captain, he enrolled at the University of Oklahoma in May, 1946, receiving his B.S. degree in chemical engineering in June 1950. He was a member of the A.I.Ch.E. Student Chapter and Alpha Chi Sigma. He is working for the Tennessee Gas Transmission Co. in Houston, with a construction survey party.

Third prize went to Charles E. Wicks a graduate of Oregon State College. A native of Oregon, he briefly attended Willamette University in Salem, Ore., leaving for three years of duty with the U. S. Coast Guard Reserve in the Aleutian Islands and South Pacific. He entered Oregon State College in September, 1946, and graduated with a B.S. in chemical engineering in June, 1950. At present he is working toward an M.S. in chemical engineering at the Carnegie Institute of Technology under a Dow Chemical Co. Fellowship and a Carnegie Institute of Technology Educational Scholarship.

Honorable mention in the student problem contest went to Herbert L. Stone, a native of Texas, and a graduate of the Rice Institute and now attending M.I.T. graduate school; Sanford Baranow a graduate of Clarkson College of Technology, and Lawrence S. Ansell also a Clarkson College of Technology graduate, where he received highest honors. Ansell is at present working as a chemical engineer with the Schering Corp.

### THREE PRIZE WINNERS IN THE A. MCLAREN WHITE PROBLEM CONTEST



R. P. BANNON



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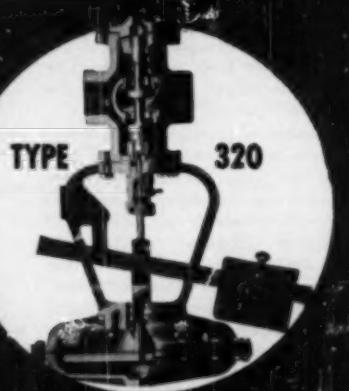
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(News continued from page 16)

### DIGITAL FAME

The Massachusetts Institute of Technology recently issued a pamphlet, "You and Your Students," designed to distill from the practice of successful teachers, principles of recognized soundness and to set them down for other teachers to study and to use. One of the paragraphs is called, "Gestures," and it reads as follows: "The fifth teaching aid is a sense of good theatre or showmanship. If the speaker has to proceed without any of the teaching aids, and has to rely on voice only, then at least he should learn to use his hands and his facial expressions both in holding interest and attention in the actual process of conveying ideas. No one who has seen in action will ever forget 'Doc' Lewis's forefinger exclamation point."

The teaching qualities of Doc Lewis' forefinger were portrayed by Henry B. Kane.



As a matter of history and nostalgia, we hope, to all M.I.T. graduates, "C.E.P." is pleased to present on this page, the sketch of Professor Lewis in action.

The booklet itself was prepared by a faculty committee under the chairmanship of Prof. Robley D. Evans.

### DE NORA MERCURY-TYPE CELLS FOR MARATHON

The first sizeable chlorine plant in the United States or Canada to use De Nora mercury-type cells with a rated capacity of 30,000 amp. will be erected by Marathon Paper Mills of Canada, Ltd., as the result of a contract signed recently by Marathon, the Leonard Construction Co., of Chicago, and Monsanto Chemical Co.

The plant, which will be located at Marathon, Ont., will be built to produce 25 tons of chlorine/day, it was announced recently by C. M. Denh, associate manager of the engineering sales department of Monsanto's organic chemicals division.

(News continued on page 24)

# MARGINAL NOTES

News of Books of Interest to Chemical Engineers

## Design Calculation in Detail

**Process Heat Transfer.** Donald Q. Kern. McGraw-Hill Book Co., Inc., New York, N. Y. (1950) 871 pp. \$8.00.

*Reviewed by George T. Skaperdas, The M. W. Kellogg Co., Jersey City, N. J.*

**P**ROCESS Heat Transfer was written "to provide fundamental instruction in heat transfer while employing the methods and language of industry." To do this, the book contains numerous fully worked out exchanger design problems in which film coefficients are computed in detail for both warm and cold sides and then combined with fouling factors to provide the basic thermal design. In many cases, the film coefficients are based on full-scale shell and tube arrangements, and use is made of tables of tube counts that are conveniently included in the Appendix. In addition, pressure-drop calculations are properly made an integral part of the design as is the case in industrial practice. These numerous detailed demonstrations of design methods differentiate the book from other books in the field and constitute its primary distinction.

Equipment treated in this manner includes: double-pipe exchangers; multi-pass shell and tube units for sensible heat transfer; condensers for pure and mixed vapors; vaporizers for water and solutions; extended-surface units; direct-contact cooling towers; agitated vessels; falling-film units; regenerators; packed beds; and trombone coolers.

A chapter on furnace design has been contributed by J. B. Dwyer and a section on evaporators by J. Meisler.

In presenting detailed design methods for so wide a field, however, it is inevitable that some of the proposed methods are somewhat arbitrary, and subject to modification. Such limitations, it would seem, ought to be a part of fundamental instruction, and it would have been desirable to indicate, for instance, that designs for partial condensation of multicomponent mixtures, or for an evaporator, are substantially less well developed than the design of a steam-heated unit for heating a fluid inside tubes. Furthermore, the tentative nature of shell-side convection coefficients might also have been made clear. While such discussion of the background of the design correlations was eliminated to provide space for the numerous examples, nevertheless, lengthy

derivatives of mean temperature difference formulas are presented in detail for a number of cases. Some of this space could have been allotted profitably to presentation of the experimental basis and limitations of the film coefficient correlations that are used in the design problems. Similarly, space occupied by fractionation calculations, equilibrium flash calculations, instrumentation, and other process discussions may also have been partially used to indicate the ranges and limits of the various correlations.

A number of questionable statements are made in the more theoretical portions of the book. The basic convection equation (heat transferred is equal to the product of coefficient, surface and temperature difference) is repeatedly called the Fourier equation. In the chapter on gases it is stated that thermal conductivity is independent of pressure, though data have been available to show large increases of thermal conductivity as the critical pressure is approached. In the discussion of pressure drop for two-phase flow no reference is made to recent data, but an unsupported, empirical method of calculation is proposed.

In general, this book should be of value to those interested in detailed methods of design calculation, particularly for tubular units, but the limitations of the available design methods are not clearly indicated.

## Water Uses in Industry

**Betz Handbook of Industrial Water Conditioning.** W. H. & L. D. Betz, Philadelphia, Pa. Third Edition. 195 pp. \$2.00.

**T**HE first part and major portion of this large book by W. H. and L. D. Betz, consultants on water problems, is given over to water treatment, which covers such items as aeration, filtration, Zeolite softening, ion exchange, deaeration, oil removal, carry-over, and embrittlement.

The second section is given over to water analysis. This section, with illustrations and directions, is written in such a way that the directions can easily be followed by those with a minimum of analytical training.

The book should be of interest to all those concerned with treating water or waste in any of its forms in the industrial picture.

## Paint Research

**Selected Government Research Reports, Vol. 2, Paints.** H. M. Stationery Office, London. (1949) 70 pp. \$1.25.

*Reviewed by R. C. Ernst, Dean of Engineering, University of Louisville, Louisville, Ky.*

**T**HE volume is a collection of reports on work carried out under the direction of the British Ministry of Supply. Eight reports are included:

**Extraction and Uses of Blood Albumen:** Blood Albumen preparation is discussed for glue; removal of color from tannin extracts; casein paint, and blood cement.

**The Viscosity of Paints and Suspensions:** Viscosity of various pigments, in paints and suspensions, are given in usable form.

**Temperature Sensitive Paints:** Selected formulations are evaluated at temperatures of 90° to 753°.

**The Effect of Surface Treatment of Brass and Yellow Metals on the Adhesion of Paint Films:** Impact tests are reported after accelerated weathering; apparatus shown.

**Tests on Some Special Base Paints for the Protection of Magnesium Alloys:** Salt-spray tests; corrosion data presented on chromate, vinyl acetate, vinyl chloride.

**Ground Flax Shives As a Substrate for Pigment Dyestuffs:** Paints of camouflage type evaluated as to brushing characteristics and color retention.

**The Effect of Heating on the Corrosion Resistance of Chromate Treated and Painted Magnesium Castings:** Data presented on salt water spray corrosion resistance of chromate primed and treated alloys.

**Tests on Phenyl Mercury Acetate As a Fungicide in Paints:** Phenyl mercury acetate with D.T.D. is evaluated with data.

A brief, well-presented collection of special information, the kind of information busy people like to have available. The material represents areas where problems are met in unusual experiences. It is not a research journal-type publication, with profound conclusions, but, if you need the kind of data represented, there it is. Meaty little reports; good readable, usable graphs and diagrams that the formulator would like to have when he needs them. A well-invested \$1.25, if you are looking for these data.

*(More Marginal Notes on page 36)*

## CANDIDATES FOR MEMBERSHIP IN A.I.Ch.E.

The following is a list of candidates for the designated grades of membership in A.I.Ch.E. recommended for election by the Committee on Admissions.

These names are listed in accordance with Article III, Section 7, of the Constitution of A.I.Ch.E. which states:

Election to membership shall be by vote of the Council upon recommendation of the Com-

mittee on Admissions. The names of all applicants who have been approved as candidates by the Committee on Admissions, other than those of applicants for Student membership, shall be listed in an official publication of the Institute. If no objection is received in writing by the Secretary within thirty days after the mailing date of the publication, they may be declared elected by vote of Council. If an objection to the election of any candidate is received by the Secretary within the period specified, said objection shall be referred to the Committee on Admissions, which shall investigate the cause for such objection, holding all communications

in confidence, and make recommendations to the Council regarding the candidate.

Objections to the election of any of these candidates from Active Members will receive careful consideration if received before Jan. 15, 1951, at the Office of the Secretary, American Institute of Chemical Engineers, 120 East 41st St., New York 17, N. Y.

### APPLICANTS FOR ACTIVE MEMBERSHIP

Henry B. Alexander, Morristown, N. J.  
George F. Borton, Philadelphia, Pa.  
Kenyon T. Bush, Plainfield, N. J.  
Richard P. Carter, Burlington, N. J.  
W. E. Cowie, Ottawa (Ont.), Canada  
George D. Creelman, Cleveland, Ohio  
R. H. Featherston, Bauxite, Ark.  
Donald C. Field, Baton Rouge, La.  
Thomas D. Heath, Westport, Conn.  
H. F. Hoerig, Buffalo, N. Y.  
J. M. Hoff, Evanston, Ill.  
Robert F. Huehner, Corpus Christi, Tex.  
H. Blandin Jones, Tuckahoe, N. Y.  
F. R. Keller, Tenafly, N. J.  
F. E. Lewis, Houston, Tex.  
Lewis C. Marino, Metuchen, N. J.  
Henry F. McEconomy, Havertown, Pa.  
Ralph H. McCormack, Brooklyn, N. Y.  
Clyde McKinley, Easton, Pa.  
William J. Minges, So. Charleston, W. Va.  
George E. Mitchell, Baton Rouge, La.  
Harmon J. Monnik, Philadelphia, Pa.  
George E. Parr, Marcus Hook, Pa.  
Marvin R. Paullus, St. Louis, Mo.  
John F. Ratzenberger, Wilmington, Del.  
Melbourne K. Richards, Wilmington, Del.  
Walter Roberts, Louisville, Ky.  
Leland F. Roy, Florence, Ala.  
E. Jackson Thomas, Pittsburgh, Pa.  
Gregory F. Vinci, New Milford, N. J.

### APPLICANTS FOR ASSOCIATE MEMBERSHIP

J. M. Dallavalle, Atlanta, Ga.  
Guy L. Honeycutt, Texas City, Tex.  
Arthur H. Laube, Lima, Peru  
John Martin Lindsley, Rochester, N. Y.  
David W. McLongan, Richland, Wash.  
Robert R. Pierce, Pennsylvania, N. J.  
H. E. Prescott, Los Angeles, Calif.  
Edward P. Schneider, Jr., St. Louis, Mo.  
Ralph W. Shrum, Wadsworth, Ohio  
Frederick Waite, Harrison, N. J.

### APPLICANTS FOR JUNIOR MEMBERSHIP

Carl F. Ackerman, Lumberville, N. J.  
Benjamin F. Adams, Jr., Newark, Del.  
D. H. Arnett, E. Orange, N. J.  
Robert J. Alfrey, Ann Arbor, Mich.  
J. H. Ashley, Chicago, Ill.  
Frank Backer, New York, N. Y.  
William G. Barclay, Louisville, Ky.  
Robert L. Bates, Miami-  
burg, Ohio  
Karl Bennung, Jr., Springfield, Del.  
A. S. Bhaduri, Salt Lake City, Utah  
Kenneth H. Bischoff, Manhattan, Kan.  
James C. Blackwell, Akron, Ohio  
Benjamin Block, Chicago, Ill.  
V. R. Bonnette, Lewiston, N. Y.  
Harvey L. Britton, Texas City, Tex.

### APPLICANTS FOR EL DORADO, Ark.

Clayton R. Carter, St. Louis, Mich.

Halvor S. Christianson, Columbus, Ohio

Paul Mahoney Coffman, Dear Park, Tex.

Victor S. Colletti, Port Arthur, Tex.

John Colonias, Elizabeth, N. J.

William R. Comstock, Port Arthur, Tex.

David Cooper, Cincinnati, Ohio

Frank H. Cornelius, Jr., Freedom, Pa.

William H. Crawford, Jr., Cleveland, Ohio

William H. Davis, Texas City, Tex.

Henry P. Donohue, Jr., Newton, Mass.

A. A. Eberle, Jr., Port Arthur, Tex.

Dorothy E. Evans, Cleveland, Ohio

Harland E. Fargo, Newark, Ohio

Charles F. Field, Boston, Mass.

Charles R. Fishback, Indianapolis, Ind.

Nathan R. Gainsboro, Long Beach, Calif.

Andrew Gandeck, Brooklyn, N. Y.

Martin O. Gernand, Baton Rouge, La.

Dale Stanley Glass, Wickliffe, Ohio

Rino L. Godino, Bronx, N. Y.

Bob Goyshor, South Haven, Mich.

Lyle J. Gross, Appleton, Wis.

James C. Hahn, Niagara Falls, N. Y.

David W. Halstead, Richland, Wash.

Ernest J. Henley, New York, N. Y.

Ralph E. Hillman, Detroit, Mich.

Nick Holloway, Jr., El Dorado, Ark.

Richard M. Howell, Lakewood, Ohio

### APPLICANTS FOR LOUISVILLE, Ky.

Eric C. Johnson, Bridgeport, Conn.

James M. Keller, Port Huron, Mich.

Thomas E. Kinder, Milwaukee, Wis.

H. W. Koopman, Jr., Spartanburg, S. C.

Loren Lafferty, Wichita, Kan.

Harry W. Lambe, W. Somerville, Mass.

Kenneth L. Landon, Springfield, Mass.

John D. Lane, Highland, Ind.

Jacques Robert La Pointe, Pittsburgh, Pa.

Herbert C. Larson, Chicago, Ill.

Gerald A. Lessells, Niagara Falls, N. Y.

Joseph M. Levy, New Britain, Pa.

H. Julian Lewis, Kingsport, Tenn.

Paul C. Lindsey, Baton Rouge, La.

Joseph Linett, Pittsburgh, Pa.

Eugene H. Lovering, Baytown, Tex.

F. Laurence Mangold, Pittsburgh, Pa.

Douglas H. Martin, Tenafly, N. J.

Michael P. Mauzy, Knoxville, Tenn.

Hugo Emil Mayer, Oleum, Calif.

Claude E. McLean, Jr., Huntsville, Ala.

Joseph F. McMahon, Jersey City, N. J.

Max F. Means, So. Charleston, W. Va.

William S. Moore, El Dorado, Ark.

Johnson Mossman, Denver, Col.

Robert B. Norden, New York, N. Y.

George R. Olsen, Houston, Tex.

James Y. Oldshue, Rochester, N. Y.

(Continued on page 26)



# NEWSCAST

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## COOPER ALLOY ANNOUNCES COMPLETELY NEW CATALOG GIVES FULL DATA ON CORROSION RESISTING STAINLESS STEEL VALVES, FITTINGS, ACCESSORIES



PLANNED to serve as a manual for all concerned with purchasing, design or maintenance of corrosion-resistant equipment, Cooper Alloy's new 48-page catalog gives complete data on all standard Cooper Alloy products. It includes engineering drawings, weights, dimensions, size ranges, materials, corrosion data, nomenclature and design information. Catalog #52 also contains easy-to-read charts covering the corrosion resisting ratings of stainless alloys, applications and other related information.

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(News continued from page 21)

### "C.E.P." BINDERS NOW AVAILABLE

For subscribers wishing to save Chemical Engineering Progress, we now offer a binder which will hold 12 issues. Monthly issues are inserted in the holder and kept in place by individual rods which insert into the fold of the publication and lock into coil springs mounted horizontally at the top and bottom of the flexible backbone.

The magazines are easily inserted and removed. The flexible backbone allows the binder to be opened flat at all times. No special preparation such as punching or drilling is required, and the binder has the appearance of a fully bound book, and yet it uses no greater space than the actual thickness of its contents.

The binder is available from Chemical Engineering Progress, 120 East 41st Street, New York 17, N. Y., at a cost of \$2.75 postage paid. It is available in red and the backbone has stamped on it in gold lettering—Chemical Engineering Progress, the volume number and the year. Any volume or year of Chemical Engineering Progress, beginning with Volume 43 (1947), may be ordered.

### S.C.I. MEDAL TO RAND

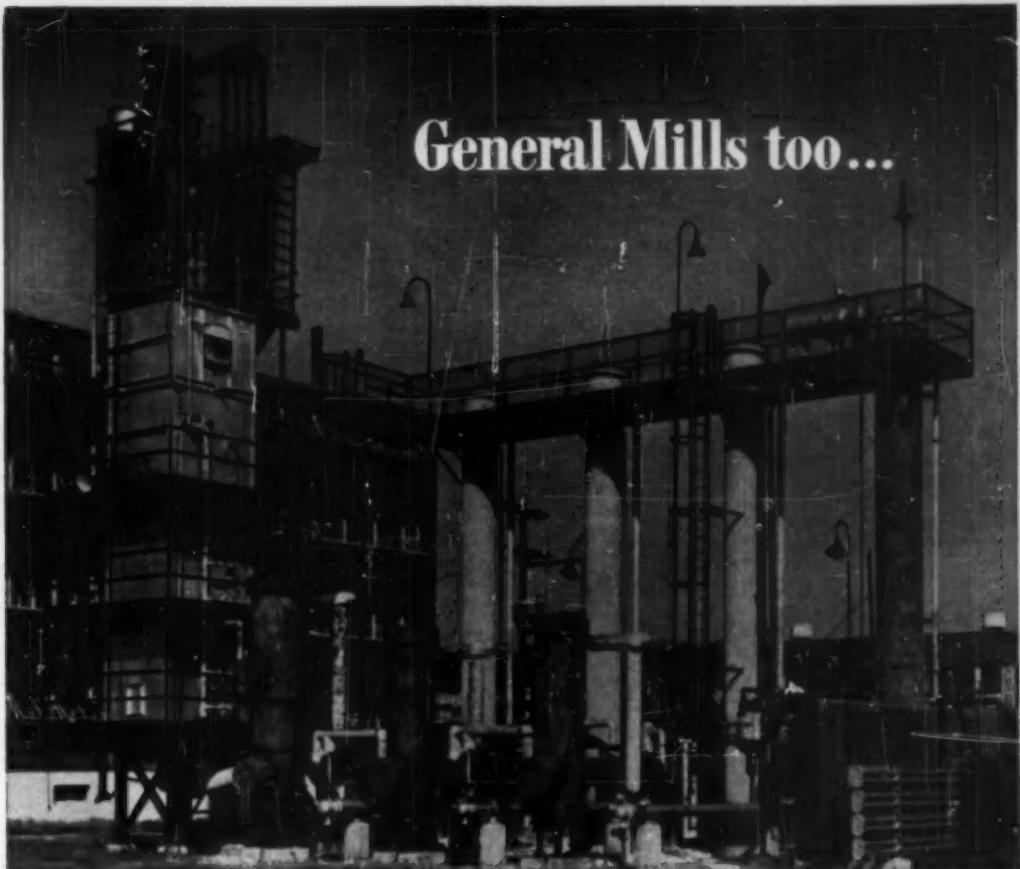
Chemical industry's obligation to identify itself with public interest was the dominant theme of the address given by William M. Rand, president of Monsanto Chemical Co., St. Louis, Mo., in accepting the Chemical Industry Medal of the American section of the Society of Chemical Industry awarded him last month. Mr. Rand, who is also chairman of the board of the Manufacturing Chemists' Association, called on the industry to assume its share of the burden of leadership in public affairs and to go beyond the mere "telling of the chemical story" to the public, which he characterized as "only a fraction of the assignment" that the industry must fulfill if it is to perform its full service.



W. M. RAND

(News continued on page 30)

# General Mills too...



## uses a **Girdler Hydrogen Plant**



Works speak louder than words  
GAS PROCESSES DIVISION

THE **GIRDLER** CORPORATION

LOUISVILLE 1, KENTUCKY

Designers, Engineers and Constructors

"MODERN FROM THE GROUND UP!" That best describes General Mills' new Chemoil plant at Kankakee, Illinois. To achieve high quality production at lowest cost, modern processes are used throughout. That's where Girdler's **HYGIRTOL\*** Hydrogen Plant comes in.

This unit produces 150,000 cubic feet of hydrogen a day for the hydrogenation of high-grade fatty acid products. The hydrogen—99.8% purity—is produced at lower cost than is possible with *any other commercial method*. Operation of the plant is continuous, automatic, instrument-controlled—another mark of modern methods!

Let Girdler help *you* improve processing efficiency. Girdler designs and builds plants to produce, purify, or use industrial and chemical process gases . . . organic compounds. Write now about your process problems.

\*HYGIRTOL is a trade mark of The Girdler Corporation

# SECRETARY'S REPORT

THE Executive Committee met in the Offices of the Institute on the morning of Nov. 10. The Minutes of the Executive Committee Meeting of Oct. 6 were approved as well as the Treasurer's report for the month of October and outstanding bills. All those candidates for membership whose names appeared in the October issue of C.E.P. were elected to the grades as indicated. Two resignations were accepted and two elections to membership were rescinded because of nonacceptance. C. R. Landgren was appointed counselor of the student chapter at the University of Maryland to succeed W. J. Huff.

The Council of the Institute met at The Chemists' Club in New York in the afternoon of Nov. 10. After some routine business, a report was received from L. W. Bass, chairman of the Committee on the Future of the Institute, which was appointed about a year ago to study and make recommendations on developments and plans of the Institute. After consideration of this progress report, it was voted that the Committee be enlarged somewhat in order to handle more effectively its duties.

Dr. Bass also reported on the activities of the Chemical Engineering Catalog Committee which were discussed at some length.

W. E. Lobo as chairman of the Program Committee also appeared before Council to discuss future plans of the Program Committee and policies regarding its activities.

Secretary presented invitation from the Cleveland Section to hold the 1952 annual meeting in Cleveland. It was voted to accept this invitation with the dates to be determined and announced.

The final draft of the Standard Testing Procedures for Heat Exchangers was presented by the Committee on Testing Techniques and Equipment Performance Standards and publication was approved. This will be made available for sale at nominal price in the near future and announcement will appear in C.E.P.

As a result of discussion of the problem of the eligibility for Student Membership of those students who were registered in curricula similar to chemical engineering but not leading to a degree in chemical engineering, the following resolution was passed:

RESOLVED that a student to be eligible for Student Membership must be enrolled in a course leading to a bachelor's degree or advanced degree granted upon the recommendation of a department or division of chemical engineering.

The annual reports of the committees were presented to Council and referred to the special committee of Council to review committee reports.

The appointments of committee chairmen for 1951 were reviewed and also the appointment of representatives with other groups. The personnel of committees will be appointed at the December meeting of Council and recommendations of the chairmen should be completed.

## KITE, A.I.Ch.E. DIRECTOR, ADVANCED BY DORR

Paul Kite of The Dorr Co., formerly assistant manager of that company's development department, was promoted to manager, Nov. 1, 1950. On that same date Anthony J. Fischer, formerly sanitary development engineer, was promoted to assistant manager of the development department, and Bryant Fitch was promoted to assistant research director under Dr. Elliott J. Roberts, the company's research director. All are chemical engineers, and members of the American Institute of Chemical Engineers, and other various technical organizations.

Mr. Kite, chairman of the Committee on Admissions of A.I.Ch.E., is well known for his work on sedimentation and classification.

Mr. Kite joined The Dorr Co. in 1922 direct from Krebs Pigment Co., after graduation from the University of Delaware and completing graduate study at M.I.T.; Dr. Fischer in 1928 direct from the University of Pennsylvania and graduate work at Rutgers; Mr. Fitch in 1944 from American Potash and Chemical Co. after graduation from California Institute of Technology. Dr. Roberts joined the company in 1929, direct from Yale, where he served as an instructor following undergraduate and graduate work.

## CANDIDATES FOR MEMBERSHIP

(Continued from page 23)

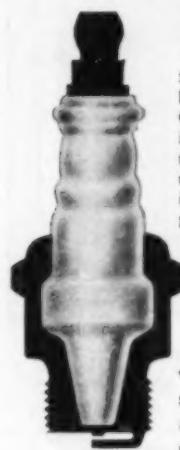
Edward B. Paille, *Baton Rouge, La.*  
Stephen G. Panson, *Wyanotte, Mich.*  
John L. Parker, *Chicago, Ill.*  
Henry E. Pence, *New Brighton, Pa.*  
Edward N. Pennington, *Bartlesville, Okla.*  
John Michael Prausnitz, *Rochester, N. Y.*  
Norman W. Pruitt, *New York, N. Y.*  
Nathan D. Puffer, *Wilmington, Del.*  
Charles F. Raines, *Pittsburgh, Pa.*  
Herbert M. Reiman, *Louisville, Ky.*  
Herman F. Reinhold, Jr., *Newark, N. J.*

Harold R. Fox, *Avon Lake, Ohio*  
R. Brown Ritter, *Orange, Tex.*  
John W. Sargent, *St. Paul, Minn.*  
Henry W. Schiessl, *Niagara Falls, N. Y.*  
John M. Schreiner, *St. Albans, W. Va.*  
E. A. Schroer, Jr., *Waterford, N. Y.*  
Robert E. Schulze, *Shokie, Ill.*  
Edward J. Serven, Jr., *Harrison, N. J.*  
C. John Setzer, *Columbus, Ohio*  
Robert S. Sheldon, *Pittsburgh, Pa.*  
Richard F. Sherman, *Wilmington, Del.*

Walter J. Sinooskie, *Pottsville, Pa.*  
Charles C. Sisler, *Annis-ton, Ala.*  
Ivan J. Sitar, *Chicago, Ill.*  
George Slutsky, *New York, N. Y.*  
Henry Smithies, *Wilming-ton, Del.*  
Blase J. Sollami, *Aurora, Ill.*  
Rosalie I. Sperling, *Rich-land, Wash.*  
Lyman S. Stanton, *Kirk-land, Wash.*  
Stuart Stern, *Brooklyn, N. Y.*  
J. A. Sturm, *Fairport Harbor, Ohio*  
Herbert Susskind, *New York, N. Y.*

Oliver E. Tarbell, Jr., *Charlottesville, Va.*  
Alfred W. Thiele, *St. Louis, Mo.*  
Frederick Torn, *Lawrenceburg, Ind.*  
Arthur L. Treisback, *Wil-mington, Del.*  
James Barry Trout, *Sea-ford, Del.*  
James L. Turner, *Richland, Wash.*  
Byron O. Wilkins, Jr., *Port Arthur, Tex.*  
Thomas J. Woerner, Jr., *Pittsburgh, Pa.*  
Donald E. Wollscheid, *Niagara Falls, N. Y.*  
John J. Youle, *Pittsburg, Calif.*  
Stanley E. Zager, *Somer-ville, N. J.*

# The salamander was a piker.



## compared with today's automobile spark plugs

Salamanders could withstand fire without harm, the ancients believed. Benvenuto Cellini wrote that his father, looking into the fire, "spied in the middle of those most burning flames a little creature like a lizard, which was sporting in the core of the intensest coals." He pointed it out as a *salamander*, never seen before "by any one of whom we have credible information."

Even if the salamander could withstand fire—a supposition long since proved a myth—its heat-resistance could not compare with that of the modern automobile spark plug.

As often as 30 times a second, the spark-plug "porcelains" in your car resist alternate exposure to cold, raw gas and 4,000° F. burning fuel.

They must also resist 8,000 volts of electricity, the pressure of extremely tight assembly, the corrosive effects of modern fuels. They must not crack or even soften.

And finally, the principal material for these porcelains must be cheap and abundant.

ALCOA Tabular Alumina—a specially refined, pure form of aluminum oxide—meets all these specifications.

So, although operating conditions have grown more severe, spark-plug insulator breakdown has almost vanished. That has been the contribution of ALCOA Tabular Alumina to the practicability of high-compression engines of today and higher ones tomorrow.

Unmatched characteristics of this inert material have already suggested other uses for ALCOA Tabular Alumina: Ceramic bodies—super-duty refractories—special cements—grinding balls—laboratory ware—"pebbles" for heat exchangers—catalyst-bed supports—and others, including many still in the "laboratory" stage.

Profitable applications in your business for the physical, chemical, thermal or electrical properties of ALCOA Tabular Alumina may be suggested by our brochure, "THE SALAMANDER WAS A PIKER." It describes ALCOA Tabular Alumina—Its Properties and Uses. Write for it. ALUMINUM COMPANY OF AMERICA, CHEMICALS DIVISION, 605M Gulf Building, Pittsburgh 19, Pennsylvania.

## Alcoa Chemicals



### ALUMINAS and FLUORIDES

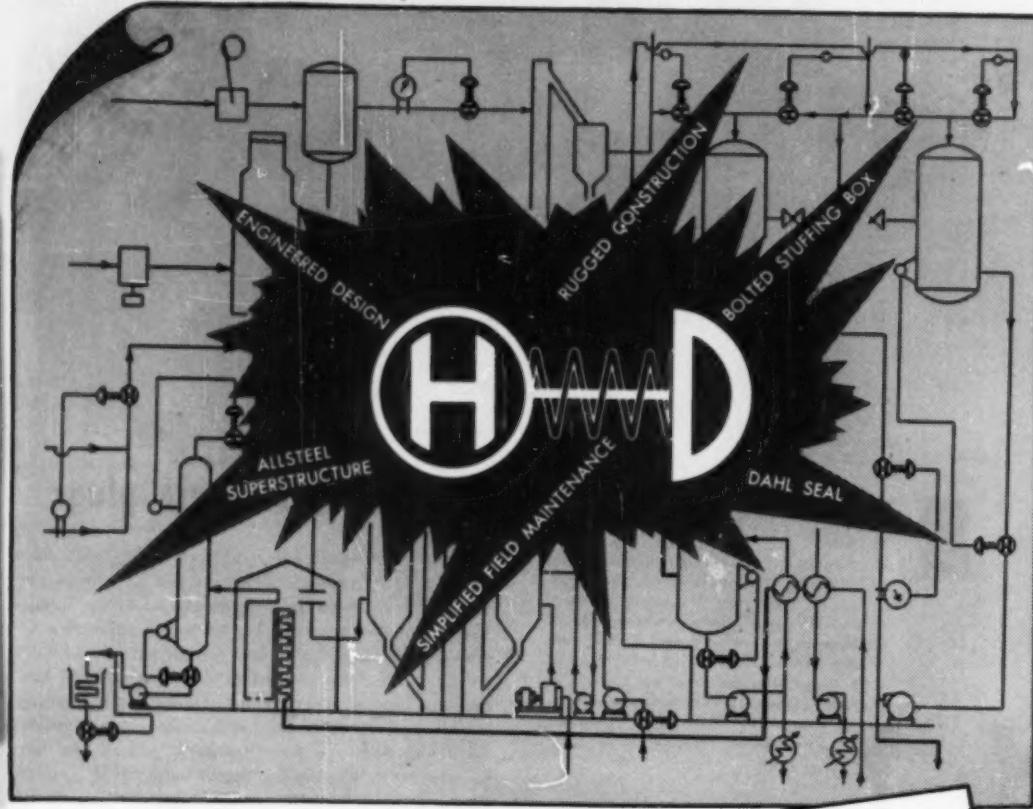
ACTIVATED ALUMINAS • CALCIATED ALUMINAS • HYDROXIDES  
ALUMINAS • TABULAR ALUMINAS • LOW SODA ALUMINAS  
ALUMINUM FLUORIDE • SODIUM FLUORIDE • SODIUM  
ACID FLUORIDE • FLUORIC ACID • CYANIDE • GALLIUM

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SEATTLE      ST. LOUIS      SYRACUSE      TOLEDO      TULSA      WILMINGTON, DEL.

In Canada: Railway & Power Engineering Corporation, Ltd.

## CHEMICALS

**1 • ALIPHATIC DERIVATIVES.** Humphrey-Wilkinson, Inc., is producing a complete line of purity aliphatics. Bulletin available which gives physical properties, general characteristics and suggested uses of 48 derivatives in the  $C_6$  to  $C_{18}$  range. Covers olefins, saturated hydrocarbons, alcohols, ethers, mercaptans and thioethers.

**2 • POTASSIUM ACETATE.** A looseleaf data insert from Niacet chemicals division of Union Carbide Corp. on potassium acetate which gives physical properties, specifications, containers, and suggested applications and uses.

**3 • 4 • 5 • KEL-F DISPERSIONS.** The M. W. Kellogg Co. offers a series of technical bulletins with information on the properties and methods of applying Kel-F (trifluorochloroethylene). (3) Deals with dispersions of the plastic, 0.1 to 3  $\mu$ . Information on stability, viscosity, etc. Application details for dipping, brushing, spraying methods, etc. (4) Covers modification of the physical properties of Kel-F molded plastic by heat treatment. To obtain varied transparencies, hardnesses, solvent resistance, dimensional stability and flexibility. (5) Explains molding techniques covering injection, transfer, and extrusion processes.

**6 • LEAD STEARATES.** Witco Chemical Co. is making a new, high-lead-content stearate as a heat stabilizer and lubricant for polyvinyl chloride resins. Data sheets cover uses, advantages, and properties.

**7 • BUTYNEDIOL.** A derivative of acetylene in a 35% aqueous solution from which anhydrous crystalline material may be isolated is newly offered by General Aniline & Film Corp. Two primary alcohol

groups and acetylene linkage make it useful in the production of intermediates.

**8 • EPON RESINS.** A new series of resins formed by reacting epichlorohydrin and bisphenol was recently developed and offered by the Shell Chemical Corp. Will find an outlet in the making of varnishes, enamels; industrial finishes for drums, machinery; industrial primers and finishes; and also to make wire enamels chemically resistant, etc.

**9 • IMPREGNATING VARNISH.** Frederick S. Bacon Laboratories have developed an impregnating varnish for electrical units which is oil resistant and also noncracking at  $-70^{\circ}\text{F}$ . Details available.

**10 • SODIUM CELLULOSE SULFATE.** A new cellulose gum of the Tennessee Eastman Corp. for use in detergents, water paints, as a sizing agent, paper coater, etc. Bulletin gives physical description, properties, viscosity charts, uses, etc.

**11 • RESORCINOL IN RUBBER.** Technical bulletin of the Koppers Co., Inc., on the use of resorcinol in fiber reinforced rubber goods. Resorcinol is used in adhesives to bond synthetic fibers to synthetic and natural rubber in belting, hose, etc. Formu-

lations and technical notes, bibliography, etc., are included.

**12 • POLYVINYL CHLORIDE FORMULATIONS.** A Monsanto technical bulletin on developing formulations for vinyl film and sheeting. Covers plasticizers, stabilizers, recommended formulas, suppliers of raw material, etc.

**14 • COLD STEEP BLEACHING.** For bleaching wood pulp, Buffalo Electro-Chemical Co. describes its new cold steep process. Covers equipment needed, bleaching formulas, cumulative results, engineering flow sheets of process equipment, etc.

**15 • ANTI-CORROSION COATING.** A company booklet from Industrial Metal Protectives, Inc., describes a one-coat anticorrosion zincilite finish. Two types are made, one requiring baking, the other air drying. Gives physical properties, treating tables, and corrosion resistant properties.

**16 • LABORATORY CHEMICALS.** A catalog of organic chemicals for laboratory use from the Smith Research Laboratories. Booklet contains listings of several hundred rare materials vital to research and industrial laboratories. Prices are given for 100 g. up to 1 kilo from Abietic acid to Xylose.

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# DATA SERVICE

**17 • HALOCARBONS.** Halocarbon Products Corp. is producing stabilized, low polymers of chlorotrifluoroethylene in the forms of oils, greases, and waxes. The use of these new products will be as bearing lubricants in high temperature installations, inert stopcock grease, sealing cements, diffusion pump oils, manometer liquids, and as softeners for chlorofluorocarbon plastics in molding and coating operations.

**18 • BRUSH KILLERS.** Chemical brush killers containing a new ester formulation, are in production by the Dow Chemical Co. The new formulation of the company makes the new Esteron products more effective on a wider variety of brush and weeds.

**19 • STEAM HOOK-UPS.** For the convenience of plant engineers in making the correct hook-up, their sixth, enlarged edition of the Sarco Steam Hook-Ups. It covers the correct steam trap selection and calculation for steam trap sizes and it has numerous pages of illustrations showing how piping, strainers, traps, pumps, kettles, dryers, presses, etc., should be vented and drained. Discusses steam heating systems; gives calculations, discusses temperature regulators, valve sizing, etc. Tables of properties of saturated steam, flange standards, pipe threads, etc., round out the bulletin.

## BULLETINS

**20 • TANK VENT VALVES.** Technical bulletin from The Vapor Recovery Systems Co. on Varec conservation vent valves and units. Covers a particular series designed as economical tank-breathing valves. Describes the use of a venturi inlet which increases vent flow through the valve over what a common nipple would pass. Charts of air flow, description of various vent units made with sizes and dimensions, prices, instruction details, etc.

**21 • ACIDPROOF CONSTRUCTION.** A descriptive bulletin of the Chem-steel Construction Co., Inc., specialists in acid-alkali-proof construction. Tells of services rendered, types of chemical equipment and plants it can engineer and design, plus illustrated series of various corrosion-proof installations that it has made.

**22 • APPARATUS AND METHODS.** A quarterly publication of E. H. Sargent & Co., of two sections, the first—technical articles and descriptions of the latest methods in the use of scientific materials. The second a catalog of the company's apparatus. Prices are given, illustrations of the usual equipment of the chemical field.

**23 • VERTICAL PUMP.** For chemical plants, paper mills, processing plants, etc., Johnston Pump Co. in conjunction with its engineering department, is offering a catalog describing the construction of vertical turbine pumps for volatile liquids, and liquids near boiling point. Uses explained, features of construction are detailed, plus diagrams.

**24 • PACKING.** For the ever-present problem of which packing to use in processing equipment, the Flex-rock Co. is offering to chemical engineers a catalog of packing products which describes all types made by it. Has a packing recommendation chart which covers steam, water, oils, air, gas, acids, caustics, solvents, etc. For reciprocating and rotary motion as well as fixed joints. Also, each type of packing is illustrated, described, and physical limitations of application given. Special types include, Teflon, Ramie, flax, rubber, asbestos, etc.

**25 • CODE COMPARISON.** A partial analysis of the 1950 A.S.M.E. code for unfired pressure vessels compared with the 1949 code has been prepared by the Downingtown Iron Works. In addition to the comparison there are data on the facilities and manufacturing equipment and the welding procedure qualifications of the Downingtown organization.

**26 • EXPLOSION-PROOF MOTOR.** A line of explosion-proof motors for hazardous locations is new with the Elliott Co. Totally enclosed fan-cooled design for use in atmospheres containing gasoline, solvent vapors, dusts, etc. Especially manufactured for chemical plants. Bulletin gives complete details of construction.

**27 • ALLOY COMPOSITION.** A data card from Babcock & Wilcox Tube Co. on the chemical compositions of seamless alloy steel tubing for heat exchangers, condensers, refin-

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ery stills, boilers, etc. Covers carbon, manganese, phosphorus, sulfur, silicon, chromium and molybdenum contents, plus trade names, ASTM specifications.

**28 • LARD MANUFACTURING.** A booklet by the Koch Supply Co. that tells the complete story of manufacturing lard, proper methods of preparing raw materials, and all the various processes involved, including preservatives, sanitation, etc.

**29 • DRAFT FANS.** Bulletin describing an extensive line of mechanical draft fans for forced and induced draft service from The Green Fuel Economizer Co., Inc. Illustrated with drawings of fan types, representative installations. Gives performance curves, efficiencies of various fans, speed, and delivery conditions.

**30 • VIBRATING SCREENS.** Link-Belt Co.'s new bulletin with details about vibrating screens for medium and heavy duty service in rinsing and dewatering a wide range of materials. The bulletin illustrates the screens, plus chart for finding the square feet of screen surface for each ton per hour of feed for various materials. Tables and drawings indicate the physical dimensions of the types available.

**31 • REMOVING ENTRAINED SOLIDS.** A manual for aid in solving the problems attending entrainment in vapor, steam, gas, or air containing tables and formulas for selection of purifiers, is a new publication of the Centrifix Corp. Cutaway views show purifier operation on various applications up to pressures of 6000 lb./sq. in. and on vacuum. Gives methods of calculating correct size.

**32 • WATER FILTRATION.** A bulletin devoted to the technique of filtering water for industrial use and making use of the Poro-Screen, Poro-Stone,

and Poro-Carbon filters of the R. P. Adams Co., Inc. General philosophy and techniques of purifying water are given, line of filters explained, as well as the operation of the equipment.

**33 • VARIABLE POWER DRIVE.** A single-phase capacitor-type electric power drive to provide infinite speed variation in any given range, is available from Sterling Electric Motors, Inc., as its Speed-Trol. Available in ratings from  $\frac{1}{2}$  hp. to 3 hp. and in 18 different maximum speeds from 2000 rev./min. down to 52 rev./min. Fingertip speed control, one-piece cast iron frame and plastic insulated wire stator.

**34 • HELIUM CRYOSTAT.** For research at temperatures close to absolute zero, Arthur D. Little, Inc., is offering a self-contained, low temperature refrigerator which can liquefy helium and maintain any temperature down to  $-270^{\circ}$  C. Liquefies 4 l. of helium an hour if liquid nitrogen is used for precooling, and 2 l. if there is no precooling. Well-illustrated, well-written bulletin available which explains operation with engineering drawings, etc.

**35 • GLASS LINING PATCHING CEMENT.** A corrosion-resisting cement for patching glass-lined vessels

subjected to heating and cooling cycles, is subject of new product data sheet of the CarboLine Co. Called Carbo-Fix 6050, the cement will repair broken glass linings for vessels where heating and cooling cycles of  $50^{\circ}$  F. to  $270^{\circ}$  F. are common. Sheet details, use and application, gives prices, etc.

**36 • RECORDING GAS GRAVIMETER.** American Recording Charts Co.'s new gas gravimeter records specific gravity of gases automatically corrected to the humidity content of air. Bulletin gives details of instrument, tells operation procedures. For use in refineries, gas plants, etc.

**37 • WHEELCO DATA BOOK.** The 1950 edition of the Wheelco data book is off the press replete with information on thermocouples, radiation detectors, resistance bulbs and other accessories for indicating, controlling and recording instruments. Prices given. Construction details of the thermocouples, physical data, information on thermocouple wire, and an excellent section on how to make a thermocouple, how to check thermocouples and pyrometers, plus data on various types of thermocouples, temperature differences and the millivoltage equivalent.

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City \_\_\_\_\_ Zone \_\_\_\_\_ State \_\_\_\_\_

**38 • ENGINEERING SERVICES.** J. F. Pritchard & Co., engineers and constructors, manufacturers of specialized equipment, tell, in an information bulletin, of the services and types of processes they are equipped to handle. Describes chemical and petroleum divisions of the company as well as equipment made.

**39 • DY-CHEK.** A dye penetration method of inspection has been perfected by Northrop Aircraft, Inc., and explained in various technical bulletins. The process requires the cleaning of the metallic surface, application of the dye penetrant, removal of the excess dye and the application of a developer which shows any cracks, hairline mars, etc., in stainless metals. The bulletin offered here lists six different technical information sheets available from the company.

**40 • BLOWER.** The Standardaire blower, built under Whitfield patents and new in displacement blowers, is described by the manufacturer The Standard Stoker Co., Inc. Is an axial flow, positive displacement blower. Bulletin gives complete construction details explaining the new-type rotors and mechanical devices incorporated. Gives test results, pictures of installations, etc.

## EQUIPMENT

**45 • FOG NOZZLE.** For producing fine, uniform fog droplets at low operating pressures, Bete Fog Nozzle, Inc., is making a new, low gallonage nozzle. Works on the "pin-jet" impingement principle. Has no internal parts. The new pin design re-

duces interference with the fog pattern. Made in 10 orifice sizes from .015 to 0.80 in. diameter with flow rates of 1 to 100 gal./hr.

**46 • MASS SPECTROMETER.** A mass spectrometer offering ten times sensitivity and a mass range up to 400, has been announced by Consolidated Engineering Corp. Uses a new ion source, which, with a new optical system provides a sensitivity of ten times more than was hitherto available. Resolving power can be adjusted during operation. Data available which explain other innovations in the model.

**47 • HEAT EXCHANGER.** The Trane Co. has introduced a new heat-exchange unit which uses no welding or soldering in the assembly for chemical process applications. Corrosion-resistant, has a mechanical joint but requires no bonding agent. Diameter,  $\frac{1}{2}$  in., stainless tubing is mechanically bonded to flat, plate-type fins by means of a bonding collar.

**48 • BARREL PUMP.** A new pull-type pump for use with liquids in drums, is offered by General Scientific Equipment Co. Fits 1½-in. and 2-in. openings on 15- to 55-gal. drums. For use in chemical plants, laboratories, etc.

**49 • BRASS CHECK VALVES.** Crane Co. announces a new line of Y-pattern, brass, swing check valves of the regrinding type. For 200- and 300-lb. pressures. Available from  $\frac{1}{4}$  in. to 3 in. inclusive, both screwed and flanged-end patterns.

**50 • MONOGAS GENERATOR.** For generating nondecarburizing neu-

tral atmospheres, consisting essentially of nitrogen plus low hydrogen and carbon content, and with carbon dioxide and oxygen and water vapor removed, is announced by the Westinghouse Electric Corp. Essentially new features of the new model are that the generator and scrubber are one unit.

**51 • NATURAL GAS COMPRESSOR.** For use in the liquefied petroleum or other industry requiring gas under high pressure, White-Roth Machine Corp. is making a new unit for compressing gas. Details available from the company.

**52 • ELECTRONIC HYGROMETER.** An electronic hygrometer that makes use of gold leaf and a chemical salt solution for control and which is usable in ranges between 20 and 93% relative humidity, is a new development of the Minneapolis-Honeywell Regulator Co. Has full temperature compensation between the limits of 50 to 120° F. and makes remote readings possible as far as 1000 ft. Operation is based on the fact that a salt cell carries a higher current in moist air and the element measures the charge of electricity between electrodes.

**53 • SINGLE TANK DEIONIZER.** For production of mineral free water, Elgin Softener Corp. announces a single tank deionizer which gives water of 5,000,000-ohm resistance, which is 10 to 100 times greater than distilled water. Uses resinous cation and anion zeolites, with the resins all contained in a single tank. Special regeneration method explained.

**54 • COMPRESSED AIR CLEANERS.** A line of separators for cleaning compressed air by means of centrifugal force, is announced by The Swartwout Co. Available in seven inlet and outlet sizes from  $\frac{1}{2}$  in. to 2½ in. Claims removal of 99 per cent of all impurities from compressed air. Contains a trap section automatically operated to release accumulated liquids.

**55 • FLOW REGULATOR.** A direct-acting regulator for control of volume of flow to processing equipment such as evaporators, etc., is announced by the W. A. Kates Co. Regulator controls flow to 0.1 gal./min. High or low pressure with corrosion-resistant materials used in making the regulator.

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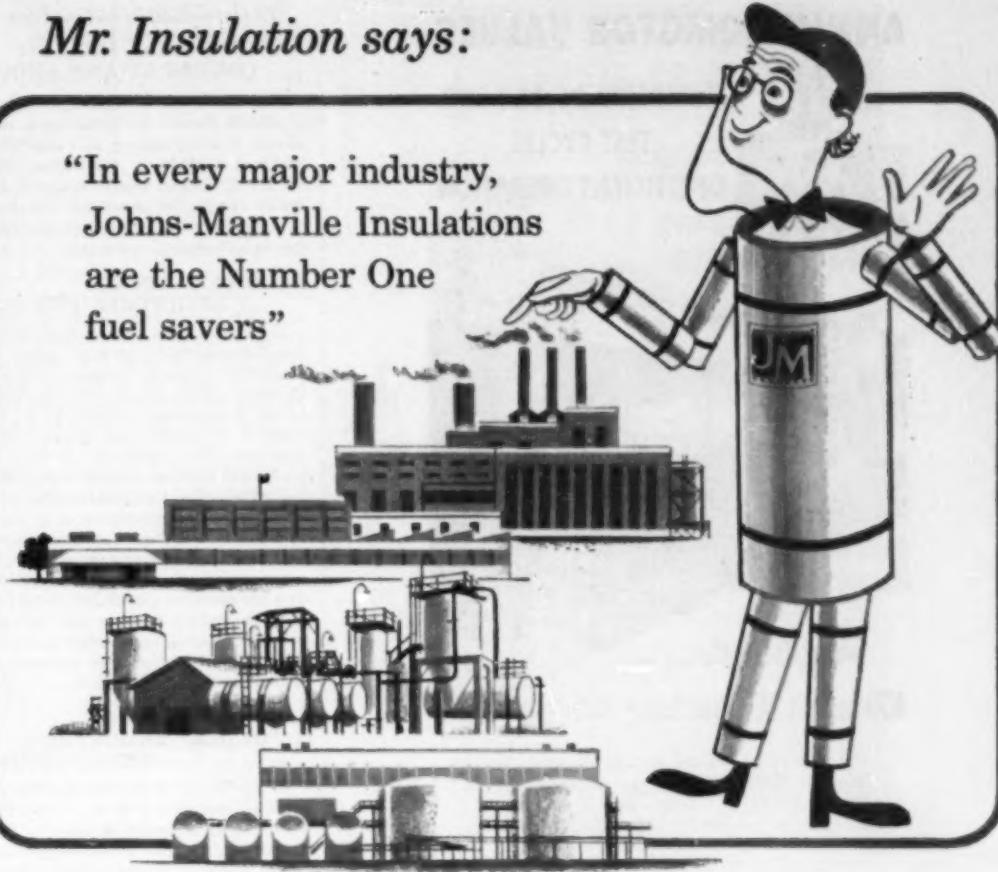
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*Reports...*

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Installed July, 1948, in a turbine test station to carry air at 100 psi and 1000° F., these valves have to date completed approximately 29,354,400 test cycles of continuous, trouble-free operation. Since their installation, none of the valves have required major overhaul. They were serviced *while in the line* . . . an exclusive feature provided by the separable valve body construction of Annin Domotor Valves.

The history of these valves is typical of Annin Domotor Valve installations all over the country. They all tell the same story . . . of Annin Domotor Valve maintenance economy, positive control and long, dependable service.

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*A new bulletin showing installation and operating features of the Domotor Valve will be sent to you upon request.*

THE ANNIN COMPANY  
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Los Angeles 23, California



*Investigate*



(News continued from page 24)

## RADIOLOGICAL HEALTH COURSE AT ANN ARBOR

The University of Michigan School of Public Health is sponsoring a new service training course in radiological health to be held at Ann Arbor, Feb. 5-8, 1951. The course is designed for Public Health Personnel and will cover most aspects of health and air pollution due to radiological emissions.

## REGISTRATION OF ENGINEERS FOR D.C.

The District of Columbia registration law for engineers, recently signed by President Truman, became effective December, 1950. It provides for registering professional engineers of the District who meet basic qualifications. Applicants may qualify on the basis of graduation from an accredited engineering school plus four years of responsible engineering experience, or 12 years of experience without formal engineering education. Examinations may be required if the record of the individual does not meet the established standards. With the registration law for the District of Columbia, registration laws now extend to every state and territory of the nation.

## A. H. WHITE AND "OLDEST INDUSTRIAL FELLOWSHIP"

A. H. White, professor emeritus of chemical engineering at the University of Michigan, recently delivered a historical paper before the Michigan Gas Association at its annual meeting, on the fellowship sponsored by that organization in Gas Engineering, at the University of Michigan.

According to Professor White, "this is probably the oldest industrial fellowship in the world." One of Professor White's first tasks as a new instructor at Michigan was to supervise this fellowship when it was first begun, and he presided over it for 43 years until his retirement. His paper gave details of the accomplishments of the fellowship briefing the work of the fellows and listing their industrial history after leaving Michigan.

## BACK ISSUES WANTED

*Chemical Engineering Progress* is still buying the April and May issues of 1947. For these we will pay 75 cents each.

We need copies of these issues and of January, 1949, in order to supply the demand for complete volumes of back issues and also to supply the demand for complete volumes for 1949. For January, 1949, issues we will pay 50 cents.

## STANDARDS BOOKLET ON A.S.A. NOW AVAILABLE

A pamphlet on, "Standards Are Your Business," has been published by the American Standards Association, 70 East 45th Street, New York 17, N. Y. The booklet explains the work of the A.S.A. and is intended primarily for the heads of American corporations who are interested in standards.

It emphasizes the value of standards on a nation-wide scope and tells how these mean great dollar-savings values to manufacturer and consumer alike.

Those who are interested in finding out more about the work of the organization, of which the A.I.Ch.E. is a member, may obtain a copy of the pamphlet by writing to the Association.

## "WIZARDS OF WHITING" RECORDING AVAILABLE

A tape recording of the Oct. 17 Cavalcade of America program, "Wizards of Whiting," is available for local section use, from the editor of Chemical Engineering Progress as part of the public relations efforts of the Institute. The program dramatizes the role of Dr. Robert E. Humphreys and Dr. William Burton in developing the gasoline-cracking processes.

The tape has been made available for use by the local sections of the Institute through Batten, Barton, Durstine & Osborn, Inc., advertising agents for the Du Pont Co. and its program, "Cavalcade of America."

The recording is an example of the dramatic possibilities in chemical engineering achievements. "C.E.P." will be glad to make available to members of the local groups, on a loan basis, the tape for play-back to audiences. Recording equipment can be rented, and it is possible to make connections into public address systems. The lead roles in the dramatic sketch are played by Lee Bowman and Ralph Bellamy.

## M.C.A. OPENS NEW YORK OFFICE

The Manufacturing Chemists' Association, Inc., has opened an office at 330 West 42 Street, New York, under the direction of Robert L. Taylor, executive vice-president. This is in addition to the Association's present offices in the Woodward Building, Washington, D. C. Activities of the new office will be devoted initially to public relations matters.

The Washington staff, under the direction of the secretary, M. F. Crass, Jr., will continue to handle committee activities. Plastic activities will also continue at this location under F. H. Carman.

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# LOCAL SECTION NEWS

## SOUTH TEXAS TECHNICAL MEETING



At the fifth annual technical meeting of this section held October 27, 1950, at the Hotel Galvez, Galveston, Tex., 400 people registered and approximately 300 attended the banquet.

Shown above from left to right are: Warren L. McCabe, President, A.I.Ch.E., who was the principal speaker—"Chemical Engineering"—1950"; W. A. Cunningham, professor of chemical engineering, University of Texas and chairman of the South Texas Section, who made the annual plaque award to J. L. Franklin, Humble Oil and Refining Co., for the best technical paper published by a member of the section during the preceding year, and R. H. Price, director of research, Pan American Refining Co., Texas City, and a past chairman of the section.

As actually presented at the meeting, the listing of the technical papers differed in a few instances from the preliminary program published in the October issue of "C.E.P." These are as follows: Howard Garrison, Pan American Refining Corp., presided over Session A instead of Frank Spuhler. At that session "Utilization of Butylene," was given by E. H. Oliver, Humble Oil and Refining Co., Baytown. Session C included a paper, "Octane Number in the Laboratory and on the Road," by A. D. Puckett, Du Pont Co., and "Effective Technical Group Speaking," by Ross Rommel, Humble Oil and Refining Co., Houston. "Opportunities in Chemical Engineering Economics," by Roscoe Stahl, Pan American Refining Corp., Texas City, was included in the Student Session.

## RHODE ISLAND SOCIETY OF CHEMICAL ENGINEERS

A group of 54 men from Rhode Island and nearby Massachusetts met Sept. 22 to discuss the organization of a Rhode Island Section of the A.I.Ch.E. This was followed by a dinner meeting on Oct. 26 at Johnson's Grill in Providence, R. I., attended by 40, at which a set of bylaws was adopted for the new Rhode Island Society of Chemical Engineers. More than 60 men have joined the group.

At the Oct. 26 meeting the following officers were elected:

*Chairman*—S. Ricklin, Brown University  
*Vice-Chairman*—K. A. Holst, Rumford Chemical Co.  
*Sec.-Treas.*—W. L. Towle, Franklin Process Co.  
*Directors*—J. K. Park, Owens-Corning Fiber Glass; R. W. Nelson, American Reinforced Paper Co.

Dr. Austin W. Fisher of A. D. Little was the speaker at the Oct. 26 meeting.

He discussed "The Place of the Chemical Engineer in Industry," emphasizing the importance of human relations factors in addition to technical ability in determining success in industry.

*Reported by S. Ricklin*

## DETROIT JUNIOR GROUP

This section held a meeting Nov. 8 in the Junior Room of the Rackham Memorial. The speakers were three men from the group itself who discussed the application of chemical engineering in their particular fields of specialization—Clifford Armstrong, Wyandotte Chemicals Corp., "Corrosion Control in the Process Industries"; Winthrop Roser, Parke, Davis and Co., "Process Development at Parke, Davis and the Pharmaceutical Industry in General," and Seymour Genden, United States Rubber Co., "Process Development at U. S. Rubber."

*Reported by W. W. Jones*

## SOUTHERN CALIFORNIA

This section held its monthly dinner meeting Oct. 17, 1950, at the University of California, Los Angeles, as guests of the department of engineering. Some 65 members and guests were present.

The program for the evening covered a tour of the engineering laboratories, including the new chemical engineering building and other departmental facilities such as the analog computers.

Following the tour, L. M. K. Boelter, professor of engineering and dean of the college of engineering, served as program chairman for three talks by members of the faculty. These included the following:

R. L. Perry, professor of agricultural engineering, University of California, "Process Engineering and the Food Industries on the Davis Campus."

W. F. Seyer, professor of engineering, University of California, Los Angeles, "Research on the Physical Properties of Hydrocarbons."

W. K. Davis, associate professor of engineering, University of California, Los Angeles, "Chemical Engineering Plans on the Los Angeles Campus."

*Reported by William J. Baral*

## BATON ROUGE

C. A. Stokes of Godfrey L. Cabot, Inc., on Nov. 17 spoke on "The Possibilities of Sonic Agglomeration in Reducing Atmospheric Contamination by Aerosols."

The second meeting of the fall season was held on Oct. 26 at which the guest speaker was Dr. Warren L. McCabe, President of the Institute, who gave a revealing talk on "The Institute—1950 Model."

*Reported by J. C. Fedoruk*

## ROCKY MOUNTAIN

The first meeting of the 1950-51 program was held Oct. 12 at Cunningham's Restaurant in Denver. Approximately 30 members and guests attended. Following dinner H. B. Van Valkenburgh, of Lamphere and Van Valkenburgh, law firm of Denver, spoke on "Patents and the Chemical Engineer."

*Reported by D. C. Davis, Jr.*

## LOCAL SECTION CALENDAR

**PITTSBURGH SECTION:** Jan. 3, College Club. **JAMES RAYNOLDS, GENERAL ELECTRIC CO.**—"Silicones."

**ROCKY MOUNTAIN SECTION:** Jan. 11, **V. F. PARRY, U. S. BUREAU OF MINES**—"Trends in the Utilization of Western Coals."

**WESTERN MASSACHUSETTS SECTION:** Jan. 18, **Panel symposium on "Material-Handling Problems and Up-to-date Methods."**

## WESTERN NEW YORK

This section joined on Nov. 7 with the Niagara Chapter of the New York State Society of Professional Engineers in a dinner meeting, which was held at the La Salle Yacht Club, Niagara Falls. Fred Piper, zone coordinator for New York State Civil Defense, spoke on "The Engineer's Role in the State Civil Defense Program."

*Reported by J. E. Troyan*

## NEW YORK

The December dinner meeting with the New York Student Chapters of New York City, was held at Churchill's Restaurant. The meeting featured a panel discussion, "On the Job Training." The principal speakers were Lauren B. Hitchcock, vice-president in charge of research for National Dairies; Alfred J. Arker, supervisor of chemical and metallurgical training program for General Electric at Pittsfield, Mass.; and Charles S. Tracy, assistant personnel manager of the Standard Oil Development Co.

*Reported by L. C. Johnston*

## EL 'DORADO CHEMICAL ENGINEERS' CLUB

"Graphic Panel Instrumentation" was the subject of a talk presented before 55 members and guests Oct. 25, 1950, at a dinner meeting in the Garrett Hotel in El Dorado. E. J. Byrne, industrial manager, Dallas division, Minneapolis-Honeywell Regulator Co., was the speaker.

Using slides to illustrate his talk, Byrne reviewed the progress in the instrumentation field up to the development of the present compact controls required for a graphic panel installation.

In the business session Dr. C. H. Davenport, president of the club, discussed the procedure for the election of the club's officers for the coming year.

*Reported by E. D. Wurster*

## PITTSBURGH

Edward C. Creutz, director of Carnegie Institute of Technology Nuclear Research Center, was the speaker at the Nov. 1 dinner meeting, held at the College Club.

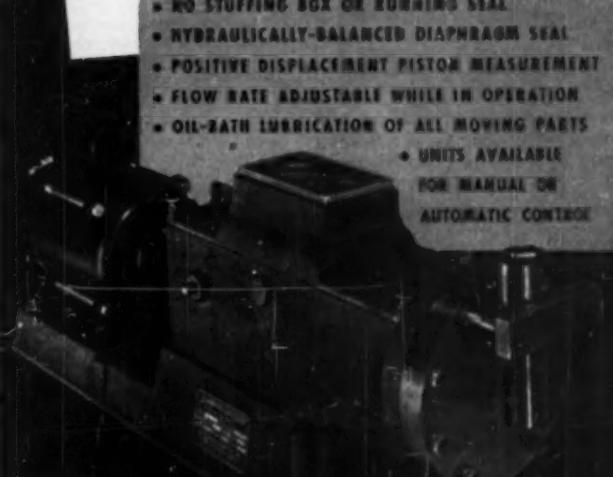
Dr. Creutz's remarks centered chiefly on constructional and engineering features of the new cyclotron being built by Carnegie Tech near Saxonburg, Pa. (Pittsburgh area). Of particular interest to chemical engineers were problems connected with the make-up of special concrete mixes for shielding purposes, the cooling and processing of circulating cooling oil for the operating unit, and high vacuum diffusion pumps.

*Reported by Hugh L. Keilner*

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- Bulletin 14**—Nozzles for metal cleaning operations.
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## FUTURE MEETINGS AND SYMPOSIA OF A.I.Ch.E.

Chairman of the A.I.Ch.E. Program Committee

Walter E. Lobo

The M. W. Kellogg Co.,

225 Broadway, New York 7, N. Y.

### MEETINGS

**Regional**—White Sulphur Springs, W. Va., The Greenbrier, March 11-14, 1951.

**Technical Program Chairman:** Walter E. Lobo, The M. W. Kellogg Co., 225 Broadway, New York, N. Y.

**Regional**—Kansas City, Mo., Hotel Muehlebach, May 13-16, 1951.

**Technical Program Chairman:** Walter W. Deschner, J. F. Pritchard Co., Kansas City, Mo.

**Regional**—Rochester, N. Y., Sheraton Hotel, Sept. 16-19, 1951.

**Annual**—Atlantic City, N. J., Chalfonte-Haddon Hall Hotel, Dec. 2-5, 1951.

**Technical Program Chairman:** Frank J. Smith, Pan American Corp., New York, N. Y.

**Regional**—French Lick, Ind., French Lick Springs Hotel, May 11-14, 1952.

**Technical Program Chairman:** W. W. Kraft, The Lummus Co., 385 Madison Avenue, New York, N. Y.

### SYMPOSIA

**Relationship Between Pilot-Scale and Commercial Chemical Engineering Equipment**

**Chairman:** Walter E. Lobo, The M. W. Kellogg Co., 225 Broadway, New York, N. Y.

**Meeting**—White Sulphur Springs, W. Va.

### Vacuum Engineering

**Chairman:** W. W. Kraft, The Lummus Co., 385 Madison Avenue, New York, N. Y.

**Meeting**—French Lick, Ind.

Authors wishing to present papers at a scheduled meeting of the A.I.Ch.E. should first query the Chairman of the A.I.Ch.E. Program Committee, Walter E. Lobo, with a carbon copy of the letter to the Technical Program Chairman of the meeting at which the author wishes to present the paper. Another carbon should go to the Editor, F. J. Van Antwerp, 120 East 41st Street, New York 17, N. Y. If the paper is suitable for a symposium, a carbon of the letter should go to the Chairman of the Symposia, instead of the Chairman of the Technical Program, since symposia are not scheduled for any meeting until they are complete and approved by the national Program Committee. Before authors begin their manuscripts they should obtain from the meeting Chairman a copy of the Guide to Authors, and a copy of the Guide to Speakers. The first book covers the preparation of manuscripts, and the second covers the proper presentation of papers at A.I.Ch.E. meetings. Presentations of papers are judged at every meeting and an award is made to the speaker who delivers his paper in the best manner. Winners are announced in *Chemical Engineering Progress*, and a scroll is presented to the winning author at a meeting of his local section. Since five copies of the manuscript must be prepared, one should be sent to the Chairman of the symposium and one to the Technical Program Chairman of the meeting, or two to the Technical Program Chairman if no symposium is involved and the other three copies should be sent to the Editor's office. Manuscripts not received 70 days before a meeting cannot be considered.

## TIDEWATER VIRGINIA CHEM. ENGINEERS' CLUB

This Club held its third program meeting Nov. 15 at the Crestwood Club in Colonial Heights, Va.

The guest speaker for the evening was H. L. Jacobs of the engineering department of the Du Pont Co. Mr. Jacobs' subject was "The Control and Disposal of Industrial Waste." The specific means by which industries are reducing stream pollution by industrial waste were discussed.

The second program meeting of this club was held Oct. 4 in the Richmond Room of the Hotel Richmond with about 50 members and their guests.

A social hour and dinner preceded a short business meeting after which

Parker D. Deans, research engineer for the Viscose Rayon research section of the Du Pont Co., spoke on "The Use of Statistical Technique in Chemical Industries."

Reported by R. L. Tilton

## OKLAHOMA

The following executive committee has been elected to finish the current year:

**Chairman**—H. L. Hays, Phillips Chemical Co.

**Vice-Chairman**—G. E. Hays, Phillips Petroleum Co.

**Sec.-Treas.**—D. H. White, C. R. Ringham, Virgil Scarth and R. D. Snow, all of the Phillips Petroleum Co.

Reported by D. H. White

## SOUTHEASTERN ASSN. OF CHEMICAL ENGINEERS

The second meeting of a chemical engineers club with headquarters in Atlanta, Ga., was held Oct. 18, 1950, with 51 persons present. Sid Kirkpatrick, vice-president, McGraw-Hill Book Co., gave a talk on "Communications, a Neglected Unit Operation of Chemical Engineering." Large delegations came from Anniston, Ala., and Copperhill, Tenn.

This club includes members from Georgia outside of the coastal area and residents of states adjoining Georgia.

*Reported by E. H. Conroy*

## ROCHESTER

A meeting was held in the Rundel Memorial Library and approximately 27 attended a dinner prior to the meeting in honor of the speaker Walter E. Lobo.

Mr. Lobo, director of the chemical engineering for The M. W. Kellogg Co., spoke on "Tonnage Oxygen Plants." He said there are four methods of producing quantity oxygen as follows:

1. Liquefaction of air with low temperature fractionation.
2. Electrolytic production.
3. Chemical production from manganese dioxide, etc.
4. Production from Cobalt Chelates.

*Reported by F. W. Kunkel*

## WESTERN MASSACHUSETTS

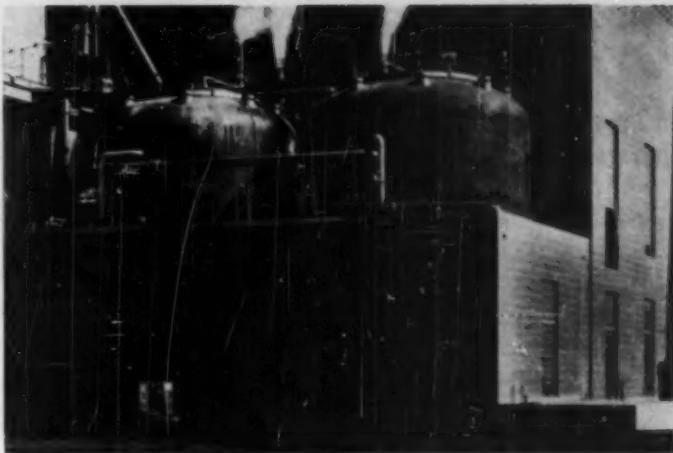
A dinner meeting (and symposium) was held at Blake's Restaurant in Springfield, Nov. 16. Brief talks were given by O. W. Greene, Pfaudler Co., and David Gold, Aerofin Corp., W. D. Comley, Whitlocks Manufacturing Co., introduced a question and answer period.

The Oct. 19 meeting was a joint one with the University of Massachusetts chemical engineering students. This meeting consisted of a trip through the University's engineering and chemistry buildings followed by a dinner meeting at which Karl Fellows, director of the University's department of food technology, spoke about problems in the food processing industry.

*Reported by R. H. Marks*

## NORTHERN CALIFORNIA

This section held a meeting Nov. 6 at the Engineers' Club in San Francisco. Total attendance at the meeting was 90. Following the dinner an address on the manufacture of sulfuric acid was made by Max Speelman, production manager, San Francisco division, Stauffer Chemical Co. He covered in detail the new acid plant which Stauffer is operating at Stege, near San Francisco, and supplemented his discussions with a color movie.



## Water Softening Unit uses Horton\* welded tanks

The Corn Products Refining Company uses water from Lake Michigan for boiler feed in the two new high-pressure steam-generating units at its plant in Argo, Illinois. The water from the lake is hard and must be treated or excessive scale would form in the boiler tubes and hinder effective heat transfer. A two-stage hot-process softener (shown above) designed by the Cochrane Corporation, is used to help make the raw lake water suitable for use in the boilers.

In the first stage, the water is pre-heated and given a treatment with lime-soda ash and a sodium aluminate adjunct. This reduces the hardness to 7 or 8 ppm. and the silica to 1 ppm. In the second stage, the water is treated with disodium phosphate, which reduces the hardness to 1 ppm.

Horton\* welded steel tanks are a good choice for this service for two reasons. The welded joints do not leak—they're made tight and stay that way.

Also, it was easy to insulate these tanks since welded surfaces are smooth—they have no lap joints or rough corners.

These water-softening tanks are typical examples of the steel plate structures we build for use at chemical processing plants. Let us submit quotations the next time you need steel plate structures of any type.

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*This close-up view of the bottom of one of the 185,000-gal. tanks illustrates the skilled workmanship required to shape heavy steel plates and the carefully welded joints that are so important in building field-erected pressure vessels. Notice also that there is enough room for operating the appurtenant equipment.*

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## MARGINAL NOTES

(Continued from page 22)

### Both From Experimental Viewpoint

The Kinetic Theory of Gases, Third Edition. Martin Knudsen. (1950). 64 pp. \$1.25.

Collision Processes In Gases, Fourth Edition. F. L. Arnot. (1950) 104 pp. \$1.25.

John Wiley & Sons, New York, N. Y., and Methuen and Co., Ltd., London, England.

Reviewed by H. G. Drickamer, Associate Professor of Chemical Engineering, University of Illinois, Urbana, Ill.

THESE little books are part of Methuen's monographs on physical subjects, and cover lectures given by the authors in British universities. The lectures covered in these volumes were delivered in the early 1930's.

Knudsen's book is essentially a discussion of the behavior of molecules under high vacuum, rather than a general exposition of the kinetic theory. He devotes much space to a discussion of his own experiments, but since these were so fundamental and far-reaching in their consequences this is hardly a limitation. The subjects covered include effusion, scattering by collision in dilute gases, thermal molecular pressure, the absolute manometer, molecular heat conduction and the accommodation coefficient, and the radiometer.

The discussion is primarily from the experimental viewpoint; there is little mathematics and only the most elementary derivations. The material is well integrated with its background and covered in an informal but authoritative manner.

For one interested in high-vacuum work this volume would provide an excellent introduction. For those concerned with the more general aspects of the kinetic theory, the book would be interesting reading, but an introductory text such as Jean's "Kinetic Theory of Gases" would prove more profitable.

Arnot's book also covers molecular collisions under high vacuum, but from a somewhat different viewpoint. He is primarily concerned with the electrical phenomena involved in such collisions. He discusses the scattering of electrons, ionization potentials and the probability of excitation and ionization, effective collision cross sections, elastic and inelastic scattering and photoelectrical processes.

The discussion is again primarily experimental in nature with only a limited amount of mathematics. The presentation is clear and straightforward. A great deal has been done, both experimentally and theoretically in this field in the past 18 years and consequently

Arnot's text is considerably more dated than Knudsen's. Nevertheless, it offers a good background for those interested in vacuum-tube phenomena, Geiger-Müller tube operation, photoconductivity, and allied fields.

### Refractories' Uses Brought Up to Date

Refractories, Third Edition. F. H. Norton. McGraw-Hill Book Co., New York, N. Y. (1950). 782 pp. \$10.00.

Reviewed by W. F. Rochow, Vice-President, Harbison-Walker Refractories Co., Pittsburgh, Pa.

THIS standard text and reference book has been revised to bring it into line with the many changes in the field of refractories. Particular improvements are the addition of new chapters dealing with Special Refractory Materials, Refractories for Nuclear Power Production, and for Gas-Turbine and Jet-Propulsion Engines. Norton's ability to write authoritatively on these subjects stems in part from his association with important governmental and other research projects bearing on them.

The subject of refractories is dealt with separately under headings of manufacturers, properties, and use. Each subject is handled competently and the volume will therefore be of great value not only to those involved in the manufacture and development of refractories, but also to those who use them in the multitude of heating and melting processes.

One of the outstanding chapters is that on drying, this being revised to cover the important research work of the last two decades. Although major emphasis is directed toward industrial kilns, it is interesting to know that this book remains probably the most important source of information on small test kiln design. This will be particularly valuable to the many newcomers in the field of refractories research. High frequency induction heating is covered in this section.

The book is not only an excellent introduction to the field of refractories, but will provide much information for all who use these industrial products.

### Books Received

Theory of the Interior Ballistics of Guns. J. Corner. John Wiley & Sons, Inc., New York, N. Y. (1950) 443 pp. \$8.00.

Increasing the Use of Feed Molasses. A Technico-Economic Report. R. S. Aries and William Copulsky. Chemonomics, Inc., New York, N. Y. (1950) 51 pp. \$2.00.

Introduction to Textile Chemistry. Bruce E. Hartsch. John Wiley & Sons, Inc., New York, N. Y. (1950) 414 pp. \$4.75.

## A Beginning of a Compilation

**Handbook of Human Engineering Data for Design Engineers.** Tufts College Institute for Applied Experimental Psychology, U. S. Department of Commerce, Office of Technical Services, Washington 25, D. C. (1950) \$5.00.

THE first systematic study of human capabilities to help in the designing of mechanical equipment is the goal of the new *Handbook of Human Engineering*. It was written by the Tufts College Institute for Applied Experimental Psychology under a research contract with the Navy.

Essentially it is a compilation of data in each of the fields of Human Engineering, including summaries of principal experiments and bibliographies. It has eight broad sections: The Human Machine and Human Engineering; The Human Body; Characteristics of Vision; Factors Influencing the Deficiency of Hearing; Skin Sensitivity; Motor Responses; Physiological Factors and Intelligence. Present plans call for the publication of supplementary data, when available, to keep the compilation up to date.

## Little Books for Big Folk

**Bergwerk-und Probierbüchlein.** A translation from the German of the "Bergbüchlein," a sixteenth-century book on mining geology, by Anneliese Grunhaldt Sisco, and of the "Probierbüchlein," a sixteenth-century work on assaying, by Anneliese Grunhaldt Sisco and Cyril Stanley Smith. American Institute of Mining and Metallurgical Engineers, New York, N. Y. 1949. 196 pp., including index. \$5.00.

Reviewed by H. R. Glennon, Manuscript Editor, *Chemical Engineering Progress*.

THE Bergbüchlein, "The Little Book on Ores," which first appeared about 1500, is the first printed work in the field of mining. Indicating what knowledge and tools are necessary for successful prospecting and the finding of ores of different metals, the appeal is primarily to the beginner with the object of interesting him in prospecting and mining as a vocation.

"The Little Book on Assaying," printed in the year 1520 (approximate), covers the assaying of gold, silver, copper, and lead with directions on how to work profitably all kinds of metal. Mrs. Sisco states that this book was written more for the goldsmith and jeweler than for the primary

producer of metals. The chapter headings, "Balances and Weights," "Assay by Touchstone," "Furnaces and Crucibles," "Cupellation," "Assay of Ores," "Parting of Gold from Copper by Means of Sulphur," "Miscellaneous Operations on Gold," and among the unclassified, "How to Harden Lead," "How to Make Wax for Gilding," etc., are all-inclusive and confirm the truth of the original blurb—"compiled with great care for the benefit of all mintmasters, assay masters, goldsmiths, miners, and dealers in metals."

The weight system contained in the Probierbüchlein is shown here in tabular form as are the fluxes used for crucible assay of ores, and the separation of gold from silver and copper by use of sulphur and antimony sulphide.

Printed and bound in attractive form with a readable letter press, the entire work including the illustrations is commendable and testifies to the indefatigable labor and research that went into the clearing up of uncertainties, the seeking of advice, and the arrangement of the material.

**Colloidal Dispersions.** Earl K. Fischer. John Wiley & Sons, New York, N. Y. (1950) 387 pp. \$7.50.

IN the preface to the book the author states that it was planned as a guide to the theory and practice of the dispersion of solids in liquid media, and that in writing the book he had in mind not only the theory of colloid dispersion, but also the technical aspects for the engineer faced with technological and production problems.

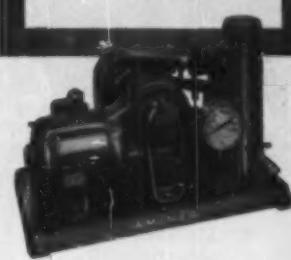
The result is a book which should appeal chiefly to the practical man, to the person faced with everyday problems in the industries which use dispersions of finely divided solids in liquid media. These industries, of course, are the paint, printing ink, textile colors, ceramic, rubber, and similar fields.

In the book Dr. Fisher covers particle size, solid-liquid interface and wetting, state of dispersed solid, rheological properties of dispersions, surface-active agents, the process of comminution, mixing, roll mills, ball mills, disc, cone, and colloid mills and dispersion by phase transfer.

Dr. Fisher does an excellent job in the book. He does not spend too much time on theory or speculative ideas. He states briefly what the considerations are in each case and then goes on to the practical aspects.

The book is replete with data and his chapters on the art of mixing and milling are excellent expositions on the practical phases of production.

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## M. W. BOYER IN POST OF GEN. MGR. A.E.C.

Marion W. Boyer, vice-president and contact director for manufacturing and chemical products operations of Esso Standard Oil Co., accepted the post of general manager of U. S. Atomic Energy Commission, effective Nov. 1. He went to Esso in 1927 from M.I.T. where he was an assistant and associate in the research laboratory of applied chemistry.

Starting as a chemical engineer in the Esso Laboratories at Baton Rouge, La., he became assistant director a year later and in 1930 was named director of the laboratories there. In 1931, he was made head of the technical division of the Baton Rouge refinery and two years later was appointed general superintendent of the plant.

Mr. Boyer was elected a director of Standard Oil Co. of Louisiana and appointed assistant general manager of manufacturing in 1935 and the following year was elected a vice-president and general manager of the refinery. He became a vice-president and director in charge of Louisiana operations of Standard Oil Co. of New Jersey, now Esso Standard, in 1945.

Born in Muncie, Ind., Mr. Boyer attended Georgia School of Technology from 1919 to 1921 and was graduated from M.I.T. in 1925 with a B.S. degree in chemical engineering. He took his Master's degree from M.I.T. the following year.

Raphael Katzen has been appointed assistant manager of the engineering division of the Vulcan Copper & Supply Co., Cincinnati, Ohio. Dr. Katzen, who has his D.Ch.E. degree from the Polytechnic Institute of Brooklyn, will have immediate supervision of the process engineering section.

J. K. Rice, formerly chemical engineer with Cyrus Wm. Rice & Co., Inc., Pittsburgh, Pa., is now treasurer and director of operations.



## PEOPLE

## IHRIG V. P. RESEARCH OF ALLIS CHALMERS

H. K. Ihrig, vice-president and director of laboratories of the Globe Steel Tubes Co., was elected vice-president in charge of research of the Allis-Chalmers Manufacturing Co., Milwaukee, Wis., effective Nov. 15.

Dr. Ihrig has already made contributions in the research field. He was cited in 1949 by the University of Wisconsin college of engineering for his contributions and inventions, particularly in the field of metallurgy. In 1947 he was awarded the Robert W. Hunt medal by the American Institute of Mining and Metallurgical Engineers for the best paper published on iron and steel research.

Dr. Ihrig, who holds 19 patents, is a native of Wisconsin. He attended Carleton College and the University of North Dakota. He received his B.S. degree from North Dakota (1919), his M.S. degree from that same institution (1920), and a Ph.D. degree from the University of California (1923).

In the past two years, Dr. Ihrig has served as a consultant for Allis-Chalmers in connection with its participation in the work of A.E.C.

## A.I.C.H.E. MEMBERS WITH MACMULLIN ASSOCIATES

R. B. McMullin Associates, consulting chemical engineers, recently announced the opening of new offices at 610 Niagara Building, Niagara Falls, N. Y. The enlarged staff now includes R. B. MacMullin, director, and member of A.I.C.H.E.; D. W. Hengerer, pulp and paper activities; P. P. Beno, formerly with Durez Plastics & Chemicals, Inc., and member of A.I.C.H.E. and R. A. Williamson, formerly with Carbide & Carbon Corp., process engineering division.

W. H. Oppelt, a member of the staff of the U. S. Bureau of Mines since September, 1947, has been appointed chief of the utilization section, lignite branch of the fuel technology division, Region V, U. S. Bureau of Mines. Dr. Oppelt is a graduate of the University of Leipzig. He is located at Grand Forks, N. D.

Edward J. Grabowski is now employed as a staff engineer with the U. S. Atomic Energy Commission at Newport, Ind. He was formerly chemical process engineer of Hydrocarbon Research, Inc., New York, N. Y.

Frederick J. Kolb, Jr., of the manufacturing experiments department of the Eastman Kodak Co., at Kodak Park, Rochester, N. Y., received the S.M.P.T.E. Journal Award for his paper entitled, "Air Cooling of Motion Picture Film for Higher Illumination," at the Society of Motion

Picture and Television Engineers recent convention at Lake Placid, N. Y. He was also elected to a fellow membership in the society. Mr. Kolb's paper was adjudged best to be published in the society's journal in 1949.

Robert C. Ellman, chemical engineer and a member of the Bureau of Mines staff since August, 1946, has been appointed acting chief of the coal preparation section of the lignite branch of the fuel technology division, Region V, U. S. Bureau of Mines. He is located at Grand Forks, N. D.

Harry Stern was appointed assistant professor of chemical engineering at The State College of Washington, Pullman, Wash., as of Sept. 1, 1950. He was formerly instructor of chemical engineering at Iowa State College.

Jerome S. Stanford, formerly general superintendent of Monsanto's plastics division at Springfield, Mass., has accepted a position as works manager of the Borden Co.'s Durite plastics division at Philadelphia, Pa.

William Klemm has joined the physical chemistry department of Kaiser Aluminum and Chemical Corp.'s division of metallurgical research. Dr. Klemm, until recently an associate professor of chemistry at Oklahoma A. & M. College, received his Bachelor's degree in 1940 from the University of Illinois and his Sc.D. from M.I.T. in 1946. His previous research has been in the study of gas turbines, jet engines and fluidized solids.

A. E. Marshall, a former President of the American Institute of Chemical

Engineers, and former president of Rumford Chemical Works, has resumed his practice as a consulting chemical engineer and now has an office in the Industrial Trust Building, Providence 1, R. I.

(More About People on page 41)



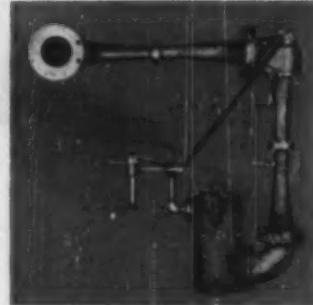
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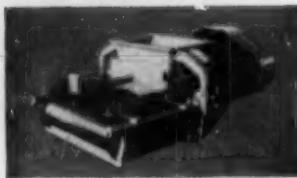
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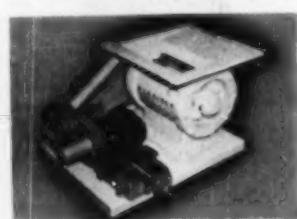
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**Research Supervisor**—Ph.D. Nineteen years' experience in petroleum derivative research and coordination of product development with manufacturing and sales. Presently director of small petrochemical research and petroleum product development laboratory. Want relocation in research supervision or administration. Box 3-12.

**Chemical Engineer**—M.S. 1949, 25, married, Top 10% of class, Tau Beta Pi, Sigma XI, Phi Lambda Upsilon. 1½ years experience. M.S. Thesis "Oxidation of Vinylcyclohexene-3." Desire position with future in research and development. Box 5-12.

**Summer Position**—Chemical engineering professor seeking industrial or academic employment in Los Angeles area for summer of 1951. Ph.D. 1944, three years industrial, four years' teaching experience. Box 6-12.

**Chemical Engineer**—M.S. 1941. Six years plant efficiency, process development, and economic analysis. Three years plant engineer, including process, design, maintenance, and construction. Six years responsible charge. Desire chemical industry development or management position. Box 7-12.

**Process Engineer**—B.S.Ch.E. 4½ years in oil refining, synthetic fuels, ammonia, and petro-chemicals. Excellent experience in process design, economic evaluation, and pilot plants. Desire responsible position with aggressive oil or chemical company. Box 9-12.

**Chemical Engineer**—B.Ch.E. 1948, 26, single, one dependent. Junior Member A.I.M.E. Currently employed as assayer. Desire position with opportunities of obtaining experience and responsibility which will qualify for engineering registration. Present location West Texas. Box 9-12.

**Chemical Engineer**—B.S.M.S. (1948-49) Chem. E. N.Y. Three years' fermentation production experience—antibiotics. Married, two children. Technical interests: process improvements through pilot plant studies, hydroponics and chemistry. Desire job as pilot plant engineer or supervisor with or without biochemical background. Metropolitan New York location not considered. Box 10-12.

**Chemical Engineer**—B.S.Ch.E. 29, family. Seven years' diversified experience organic chemicals; process development, design, plant and product cost estimating, and production. Desire responsible position as development or process engineer. Box 11-12.

**Chemical Engineer**—B.Ch.E. 1943, single, no limitation on location. Seven years' experience in development, design, and operations in the industrial gas business. Desire a responsible production position. Box 12-12.

**Chemical Engineer**—B.S., M.S., Princeton. Six years' engineering experience chiefly production supervision and development in polymerization and acetalization. Prefer production work in any field. Box 13-12.

**Research Chemical Engineer**—27, M.Ch.E. P. E. N. Y. State. Six years diversified experience including one year pilot plant development. Four years inorganic process development. Thorough knowledge thermochemical, physical chemical and process calculations. Experience with all techniques for conceiving and evaluating new chemical processes. Box 14-12.

## CLASSIFIED SECTION

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**Chemical Engineer**—M.S., Columbia, 1950. Excellent scholastic record, Tau Beta Pi, Sigma Xi. Over one year varied experience in responsible position with small company. Veteran, single, 23. Desire position in development or technical service. Box 17-12.

## PEOPLE

(Continued from page 39)

### STICKLEY, DEVELOPMENT ENGINEER AT MONSANTO

Joseph F. Stickley, assistant manager of Monsanto Chemical Co.'s plant at Monsanto, Ill., joined the development department of the company's organic chemicals division at St. Louis, Dec. 1.

A principal duty of Mr. Stickley, in the newly created post of development engineer, will be to review, from an engineering standpoint, development items in their early stages and before they are far enough along to justify actual plant exploration.

During the war, Mr. Stickley was manufacturing superintendent in charge of the Monsanto-operated Chemical Warfare Service plant which he helped to design and construct. He was appointed assistant plant manager in 1946.

A native of St. Louis, Mr. Stickley graduated from Washington University in 1918 with a B.S. degree in chemical engineering. He has been with Monsanto since 1920.

**R. F. Cockerill** is now production supervisor with the Du Pont Co. in Victoria, Tex. He went there from Charleston, W. Va., where he served the company as assistant supervisor.

**John S. Carpenter** has been transferred from Pittsburg, Calif., where he was employed as a research and development engineer, Dow Chemical Co., to the company's Great Western division at Concord, Calif. At Concord he is superintendent of the organic chemicals department.

**George J. Azadian**, formerly junior chemical engineer, Weber Showcase & Fixture Co., Los Angeles, Calif., is now affiliated with C. F. Braun & Co., Los Angeles, engaged in project engineering.

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**ENGINEERING MATERIALS ENGINEER:** Five to ten years' experience in Engineering work dealing with corrosion problems, metallurgical investigations, selection and specification for rubber, ceramics and plastics for various uses, fabrication, for

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**INSTRUMENTATION ENGINEERS:** Five or more years of progressively difficult experience in Instrument Research Development or design. Must have broad and thorough knowledge of instrument theory and application. Should have some knowledge of Chemical Equipment and its operation. Must be graduate.

**MATERIALS HANDLING ENGINEERS:** Must have eight to twelve years' broad and thorough experience with operation, uses of all types of materials handling equipment. Must be familiar with chemical equipment and its operation. Also interested in such engineers with specific experience in wide range of bulk materials handling. Must be graduate.

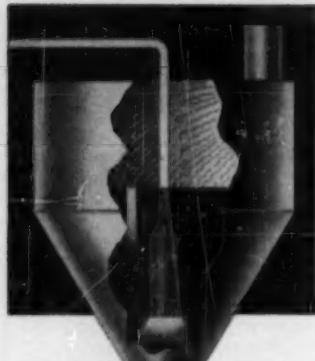
Give experience, education, age, references, personal history, salary received and salary expected. Please be complete and specific.

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### A.I.CHE. MEMBERS ADDED TO GENERAL ANILINE

Three New Jersey chemical engineers, members of A.I.Che., were added recently to the production and engineering staffs of the Grasselli Works division of General Aniline and Film Corp. These men and their new positions are:

Clyde McKinley has been transferred from the company's central research laboratory, Easton, Pa., to assume the duties of chemical engineering assistant to the manager of the area comprising the special products department and the sulfur colors and textile auxiliaries department. Dr. McKinley will act in a liaison capacity between production, development and engineering in promoting the design and installation of new projects in the two departments. Dr. McKinley received a Doctor's degree from the University of Michigan in 1943.

Ralph C. Barley has been named senior chemical engineer in the chemical engineering department. A graduate of Drexel Institute in 1941, he also has been a postgraduate student at M.I.T. and Case Institute.

John C. Rabetz has been appointed to the engineering department staff as a project engineer. A graduate of Brooklyn Polytechnic Institute in 1947, he has been continuing his chemical engineering studies at the Institute.

Seymour C. Hyman is now affiliated with the department of chemical engineering, The City College, New York, N. Y. He was formerly chemical engineer, general development laboratory, U. S. Army, Signal Corps., Ft. Monmouth, N. J.

Alphonse Pechukas has been named engineering manager for the chemicals division of the General Electric Co.'s chemical department. Formerly director of research for the Columbia chemical division of Pittsburgh Plate Glass Co. at Barberton, Ohio, Dr. Pechukas is a graduate of the University of Chicago and holds a B.S. and Ph.D. degree in chemistry.

Edward R. Hagan, formerly assistant works manager with the Du Pont Co., Arlington, N. J., recently retired. A graduate of the College of the City of New York Mr. Hagan first became associated with the Du Pont Viscoloid Co. in 1916 as chemist in charge of the control laboratory in Arlington. Subsequently he became division head of the Research Laboratory and still later was in charge of the manufacture of pyroxylin and the development of equipment for nitration, purification, etc. In 1930 he was advanced to the position of chemical superintendent of the Du Pont Viscoloid Co., Leominster, Mass.

### R. A. BENZAQUIN GOES TO CELANESE

Richard A. Benzaquin, assistant to the Executive Secretary of the American Institute of Chemical Engineers since 1945, is now associated with the chemical division of the Celanese Corporation of America. Mr. Benzaquin is serving as a chemical engineer in the recently organized operations-control department located in the New York office.

Mr. Benzaquin is a graduate of M.I.T. (1941) and holds the degree of B.S. in chemical engineering. He was at one time associated with the Koppers Co., Inc., Pittsburgh, Pa., as a chemical engineer.

J. F. Honstead, formerly chemical engineer of the General Electric Co., is now engineer with the nucleonics division in Richland, Wash. Prior to his affiliation with General Electric Co. he was assistant professor in the department of chemical engineering, Kansas State College, Manhattan, Kan.

Roger Williams, Jr., has opened a consulting office in New York City. He is associated with William Sherwood and Frank R. Clarke, Jr., as consultant to the chemical industry in an engineering, economic, and public relation capacity. Mr. Williams was formerly with the McGraw-Hill Publishing Co. as an editor on Chemical Engineering.

Charles F. Booth is president of the Covington Fertilizer Co., Andalusia, Ala. This is a new company recently formed for the purpose of engaging in fertilizer mixing and insecticide blending. He was formerly associated with the Monsanto Chemical Co., Elmore, Ala.

Irving Roberts, formerly with the Elliott Co., in charge of the development of tonnage oxygen and other low-temperature processes, has entered the consulting field specializing in gas separation, low-temperature plants, catalytic oxidation, etc. Prior to his service with Elliott he had served as a group leader in the Manhattan Project and as a chemical engineer with Weiss & Downs, Inc. Dr. Roberts' office is located at Jeannette, Pa.

## Necrology

### ROLAND WOODWARD

Roland Woodward, engineer on plant and equipment design and operation, Atlas Powder Co., Wilmington, Del., died recently.



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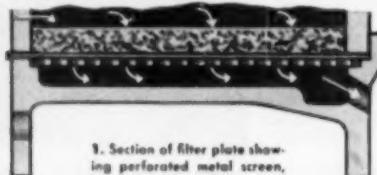
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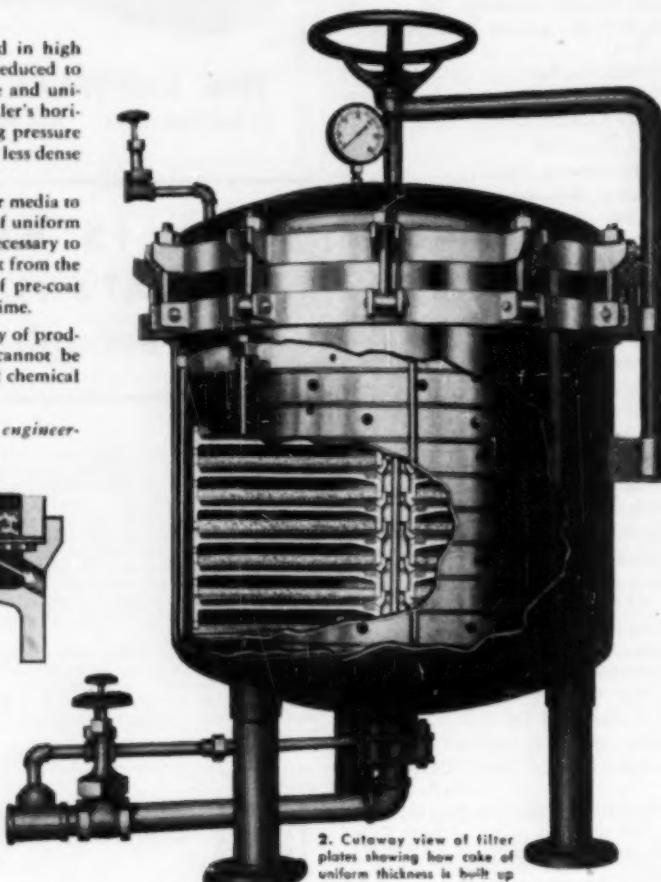


1. Section of filter plate showing perforated metal screen, filter media, and filter cake.

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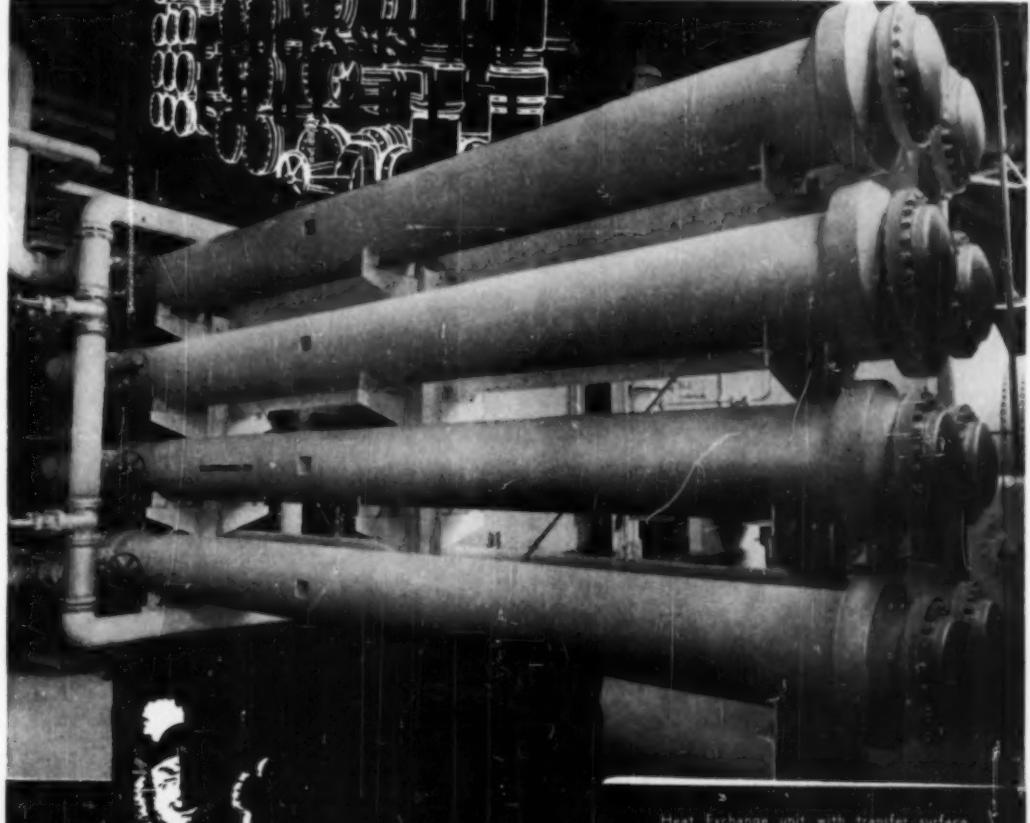
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2. Cutaway view of filter plates showing how cake of uniform thickness is built up on each plate.



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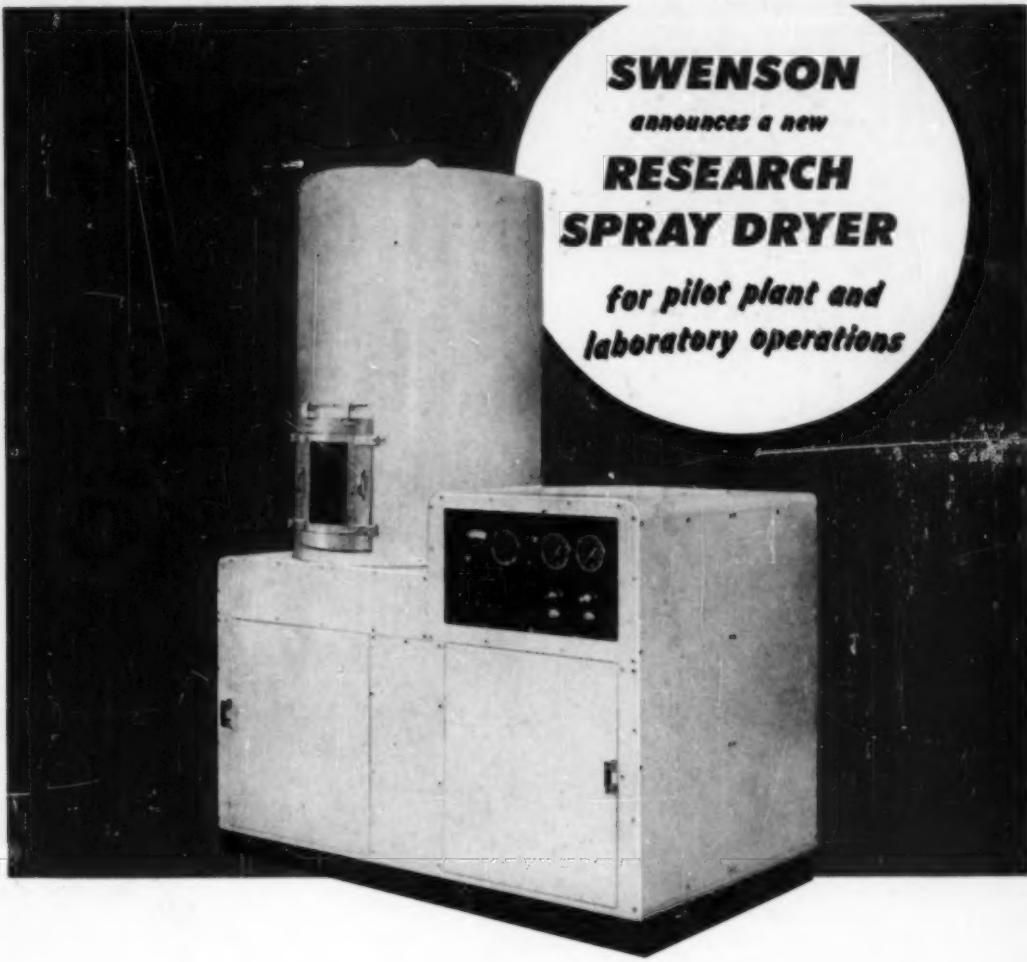


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